

Computational Re-interpretation of Heritage Architecture

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Preface

Born with a passion for arts and attracted by science, I have a dream to be an architect. Ever since I was a child, I was always fascinated by the magnificent architecture such as the Eiffel Tower, the Golden Gate Bridge, and the Forbidden City, which towered into the realm of the art rather than merely the combination of concrete and rocks. As I grew up and finished my undergraduate study, I also realized the significance of the science hidden in those beautiful figures and found that architecture was what I truly wanted to pursue for further study, and a career in the future.

I majored in physics, minored in visual arts during my undergraduate years, which not only enlightened me the mysterious rules of the nature, but also engrained vision of appreciation and quest of beauty on my soul. And ultimately, I have also found my interest in the architecture in my studies. During those years, I obtained rigorous training in mathematics and physics, as well as an introduction to programming languages. These transferable skills bring me the advantages when later I move on to start my architecture journey, especially, the computational area.

Since I came from China, (a country with long history and precious antiques), and studied in Hong Kong (a place Western and Eastern cultures meet) for my first degree, I appreciate beauty of different cultures and am bilingual. I have a fervent desire to become an expert in the domain of ancient or traditional architecture and devote myself to the retrieval of historic sites. Whether it is Pompeii's relic or Yuanming Palace's ruin, Solomon's devastated shrine or the nameless Taoist's ravaged temple, I can always see through the vicissitudes and the decay of the history and observe the ancient beauty with reverence.

When I took my Master's degree in architecture, I attempted to recreate a piece of traditional Chinese architecture in a CAAD module for a first time. Ever since then, I could not stop thinking how to apply the computational skills on this fascinating target to interpret and revive our traditional values and styles. It was this that spurred me to start my PhD research on this topic.

Starting from the unfolding of *Ying Zao Fa Shi*, I always feel I am communicating with Jie Li, one of the greatest architects in the world from a thousand years ago. His design principles, literature, and masterpieces have affected China, even the world, for more than ten centuries. If at his time, computer was invented, what would be the story? With such a curiosity in mind, my PhD journey is full of wonder and enjoyment.

Table of Contents

Acknowledgements.....	i
Preface.....	iii
Table of contents.....	v
Abstract.....	ix
Chapter 1 Introduction	1
1.1 Background	2
1.1.1 Background of China and traditional Chinese architecture	2
1.1.1.1 Brief history and development of architecture.....	2
1.1.1.2 Current status of research.....	26
1.1.1.3 Current status in urban planning and architectural design	28
1.1.2 Relevant methods and techniques in heritage studies	45
1.2 Aims and objectives	55
1.2.1 Research question and research value.....	55
1.2.2 Research objectives	56
1.3 Methodology	58
1.4 Potential outcomes	61
1.5 Limitations	61
Chapter 2 Research context.....	65
2.1 Historical references.....	65
2.1.1 <i>Ying Zao Fa Shi</i>	65
2.1.2 <i>Gongcheng Zuofa Zeli</i>	68
2.1.3 Other relevant historical references	69
2.2 Liang's research on the two rulebooks	71
2.3 Utilisation of the historical references in research.....	78
2.4 Parametric design and Grasshopper on a Rhinoceros	81

2.4.1 Parametric design	81
2.4.2 A Grasshopper on a Rhinoceros.....	83
2.5 Other relevant research.....	83
2.5.1 Conventional approach to <i>Ying Zao Fa Shi</i>	83
2.5.2 A comparison between Chinese architecture and Western architecture	89
2.5.3 Pattern language	90
2.5.4 Shape Grammar approach to <i>Ying Zao Fa Shi</i>	91
2.5.5 Research of proportion on traditional Chinese architecture.....	94
2.5.6 Digital representation of the Yuanming Palace.....	94
2.5.7 Digital fabrication of Japanese joint.....	97
2.5.8 Parametric approach to <i>Gulou</i>	98
Chapter 3 Case study 1—floor plan	101
3.1 Description of the ancient floor plan system.....	102
3.2 Rectangular shape floor plan.....	105
3.3 Utilisation of <i>Cai</i> and measurement units for floor plan.....	107
3.4 Parametric models of the floor plan	110
3.4.1 Attempt 1—basic model.....	111
3.4.2 Attempt 2—connection with <i>Cai</i>	116
3.4.3 Attempt 3—column positions and podium	121
3.4.4 Attempt 4—optimisation.....	129
3.4.5 Attempt 5—further optimisation	132
3.5 Comparison with extant building data	134
3.6 Discussion, conclusion and future work	136
Chapter 4 Case study 2—section	141
4.1 Description of the ancient style section.....	142
4.2 Parametric attempt 1—example based models with column focus.....	144

4.2.1 The understanding of <i>ting tang</i> section	144
4.2.2 Parametric models with column focus	147
4.2.3 Variations	152
4.2.4 Discussion	153
4.3 Parametric attempt 2—example based models with roof focus	154
4.3.1 The understanding of the ancient style roof	154
4.3.2 Parametric models with roof focus	156
4.3.3 Discussion	164
4.4 Parametric attempt 3—algorithm based models	164
4.4.1 Three layers of the section	165
4.4.2 Parametric models of the three layers of the section	172
4.4.3 Variations	179
4.4.4 Discussion	182
4.5 Discussion, conclusion and future work	182
Chapter 5 Case study 3— <i>dou gong</i>	187
5.1 Description of <i>dou gong</i>	189
5.2 Top-Down method in parametrics	193
5.3 Bottom-Up method in digital fabrication	195
5.3.1 The digital representation of the <i>dou gong</i> components	195
5.3.2 The digital fabrication of the paper components	200
5.3.3 Practical problems and modifications	203
5.3.4 Assembly of the fabricated components	206
5.3.5 Discussion	209
5.4 Summarized information for parametric modelling	214
5.5 Bottom- Up method in parametrics	227
5.5.1 Attempt 1	228
5.5.2 Attempt 2	233

5.5.3 Attempt 3	236
5.5.4 Discussion	246
5.6 Discussion, conclusion and future work	246
Chapter 6 The integrated models of traditional Chinese architecture	251
Chapter 7 Applications of the research findings	257
7.1 Newly generated rule based floor plans	257
7.2 A Master's degree project	260
7.3 A practical project of a Chinese garden	262
Chapter 8 Discussion.....	271
8.1 Comparison with Shape Grammar approach	271
8.2 Comparison with conventional interpretation	274
Chapter 9 Conclusion	277
9.1 Response to aims and objectives	278
9.2 Limitations	279
9.3 Contribution to knowledge.....	280
9.4 Future work suggestions.....	281
References	283
Appendix 1 Gherkin project in the 2015 Constructionarium	292
Appendix 2 The floor plan questionnaire and diagrams of the survey	300
Appendix 3 Published papers.....	312
eCAADe 2013 conference paper:	312
eCAADe 2014 conference paper:	321
Epilogue	333

Abstract

Computational Re-interpretation of Heritage Architecture

Di Li

This thesis presents research in which a set of contemporary computational digital techniques have been applied to investigate and interpret traditional Chinese architecture. The techniques involve algorithmic representation, digital modelling and digital fabrication. The research provides a methodology that can be utilised for future research employing the digital techniques in the context of understanding, investigating, interpreting and representing traditional Chinese architecture.

The ancient rulebooks that describe the traditional Chinese architectural styles and construction technologies are used as the basis for the algorithms and parametric rules and the application to the modelling and fabrication process. Building on the work of producing systematic analysis on both rulebooks and contributing knowledge from extant buildings, the possibility of modelling traditional Chinese architecture using digital techniques is proposed and tested. This augments research already undertaken by architectural historians (who provide traditional approaches and analysis) by offering a new perspective to understand and recreate the Chinese style, as well as solving difficulties that traditional methods struggle with.

The research is significant as it demonstrates how digital techniques can advance knowledge and understanding of significant Chinese architectural styles, especially considering a large number of heritage buildings are lost or damaged, as well as there is a lack of systematic and complete records. Consequently, this enhanced understanding can then be used to rediscover, restore, refurbish and recreate the traditional Chinese architecture.

The research is significant as it also illustrates how digital techniques, especially parametrics, can be applied to a novel target, traditional Chinese architecture, which is beyond the common area of complicated shapes of contemporary architecture that they are usually applied to. Consequently, this attempt extends the function of digital techniques and bridges the gap between the traditional Chinese architecture and contemporary parametrics.

Three case studies of significant elements in the understanding traditional Chinese architecture are used to present and advance the methodological process provided. These are the parametric recreation of the floor plan, the parametric interpretation of the design principles of the *ting tang* and *dian tang* sections, and the study of a typical Chinese joint structure, the *dou gong*. Each case study offers its own contribution to achieve the two significances.

An example of the integrated digitally represented conceptual model is then given based on the three case studies. Three applications are also included to further prove the findings of this research.

The findings illustrate how contemporary digital techniques can be used to augment and enhance knowledge of traditional Chinese architecture by turning descriptions and definitions into rules and algorithmic representations through the study of the rulebooks and the process of digital modelling. During this process inferences have to be made as representational source data such as architectural drawings are almost always incomplete and ancient language used in rulebooks is hard to understand accurately. The key here is the systematic and logical advancement that digital techniques bring when compared against design styles of architecture that was established in a pre-digital context.

The findings also demonstrate enhanced understanding of using digital techniques to investigate and interpret traditional Chinese architecture. During this process, the cultural aspects, Chinese history, ancient politics, Chinese traditions and styles are all integrated into the consideration and representation of the digital techniques, which add new inspirations to the contemporary computational techniques.

Chapter 1 Introduction

In architecture, to translate original design ideas into a finished building, mediating devices are an essence to communicate the design. Unlike other types of artworks, in the vast majority of cases, it is usually not feasible or practical to make full-scale physical prototypes of architecture. Therefore, the use of representational techniques, such as two-dimensional drawings and three-dimensional models are necessary. These techniques enable the distribution of the design ideas from one designer to everyone.

Such mediating devices have developed into the digital realm with the widespread introduction of computer aided architectural design from the 1980s onwards (Webb, 2012). Since this, the process of constructing digital representations of architecture has become increasingly complex, offering the potential to be exploited as a tool in a research context (Brown & Knight, 1995).

China is one of the Four Great Ancient Civilizations and its traditional Chinese architecture plays a significant role in the world's architectural heritage. This country, with over 5000 years of history and vast territory, boasts remarkable architecture from all dynasties and in different regions. Unfortunately, almost all the buildings constructed before the Tang Dynasty (618—907) have disappeared in China although some remained in Japan. Also the records and instructions left are few though images and some drawings could be found. And there are some buildings from the period from the Tang Dynasty to the Qing Dynasty (1616—1912) remaining, but some have been badly damaged or destroyed and the rest in differing states of repair. Unfortunately, the research materials are fragmentary and sometimes incomplete, which leave the traditional Chinese architecture largely unknown to the modern world, but also creates difficulties in protecting and inheriting traditional Chinese styles.

In such situations, digital techniques could be used to visualise the damaged, destroyed or unbuilt works of architecture and remote archaeological remains (Mitchell, 1992). Such investigation enables a clearer understanding of how these buildings would have looked like, which further enables the understanding of the styles and possibility of recreation. On the other hand, during this process, a novel target—traditional Chinese architecture will also enhance the functional research of digital techniques by representing a less common style.

1.1 Background

To link the digital techniques and traditional Chinese architecture together, both aspects are reviewed as a background to begin with.

1.1.1 Background of China and traditional Chinese architecture

Architecture cannot exist in isolation from lifestyle and culture. It is the natural environment and social environment that determines the architectural styles and characters. With the extremely long history in the ancient periods and rapid development in the modern period, people's perspective of evaluating the traditional architecture is changing, as well as the research methodology and practical planning. When studying architecture, two references are essential—literary records and extant buildings. Based on this, the following sections will briefly describe traditional Chinese architecture from ancient times until now.

1.1.1.1 Brief history and development of architecture

Chinese history spans over 5000 years, including ancient period, feudal dynasties and modern period macroscopically. Figure 1 illustrates the chronological diagram indicating the brief history of China. Figure 2 further shows the feudal dynasties chronologically and the two dynasties (in the red square boxes) in which the two rulebooks were compiled. The two rulebooks will be introduced in details in Chapter 2.

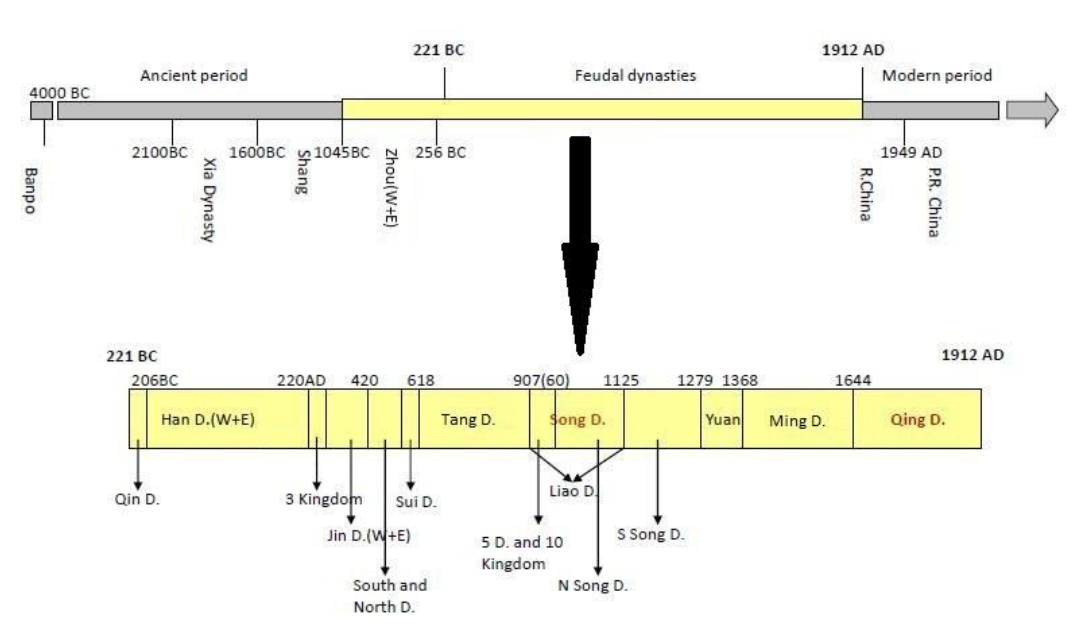


Figure 1. Chinese history in chronologic order

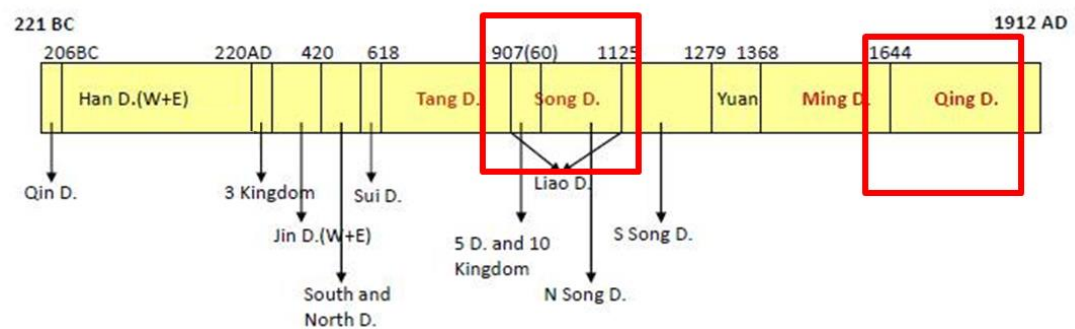


Figure 2. Feudal dynasties

In order to better describe the architecture mentioned below and relate their characters with the locations accordingly later, a map of China is shown in Figure 3.



Figure 3. Map of China (Stephen, 2007)

About 6000-7000 years ago, the first timber frame house appeared in Zhejiang province Yuyao Hemudu village. From this historical site, it has been found that the house was 23m in width and 8m in depth with columns, beams, and especially, tenon-mortise connections (see Figure 4) (Pan, 2009, p. 17). This is believed to be the earliest manmade timber structure house and the earliest example of tenon-mortise technology. These two features have been passed on since then and become the spirit of the Chinese style in the following thousands of years. The tenon-mortise technology is the origin and basis of the later dou gong structure (a typical Chinese joint) which will be introduced in details in Chapter 5. Considering the character and load limitation of the wood material, the scale of the house is large for the time. But also due to the feature that wood is susceptible to damage by the natural environment, it is hard to conserve. This is one of the reasons that much important architecture was lost and few still exist.

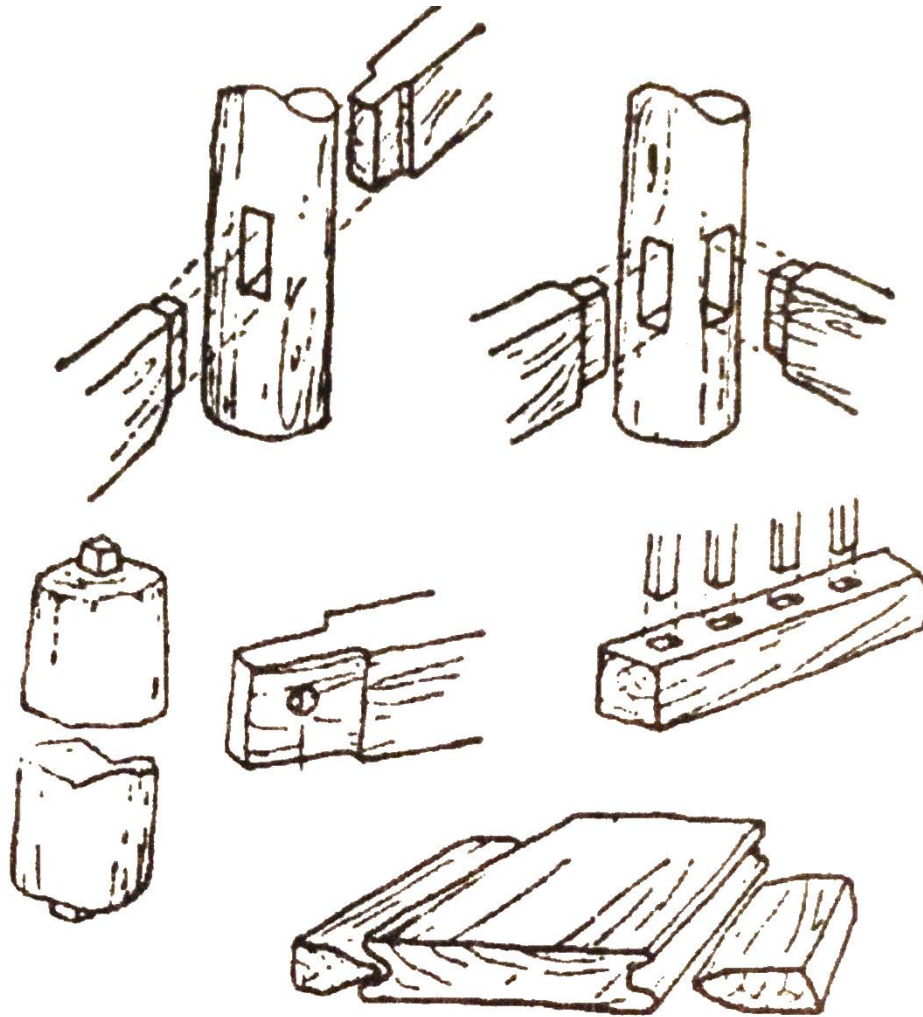


Figure 4. Zhejiang province Yuyao Hemudu village historical site tenon-mortise connections (Pan, 2009, p. 18)

The Xia Dynasty (2070BC-1600BC) is the first slavish dynasty in China. There was no written language at this time, so any evidence is anecdotal or in the form of found objects. Archaeologists are still discovering its mysteries. In the historical sites found so far, it is still debatable which appeared in Xia Dynasty. However, it is presumed that in Henan province Yanshi Erlitou, the capital city palace by the end of Xia Dynasty is from this period (see Figure 5) (Pan, 2009, p. 21). The plan shows that the columns are aligned at all the four edges, and all the bay width of each bay are equally divided (here basically means, the distance between the front columns and back columns is the same, and more definitions of the floor plan will be discussed further in Chapter 3), which indicates the timber frame technology has reached a high standard at that time.

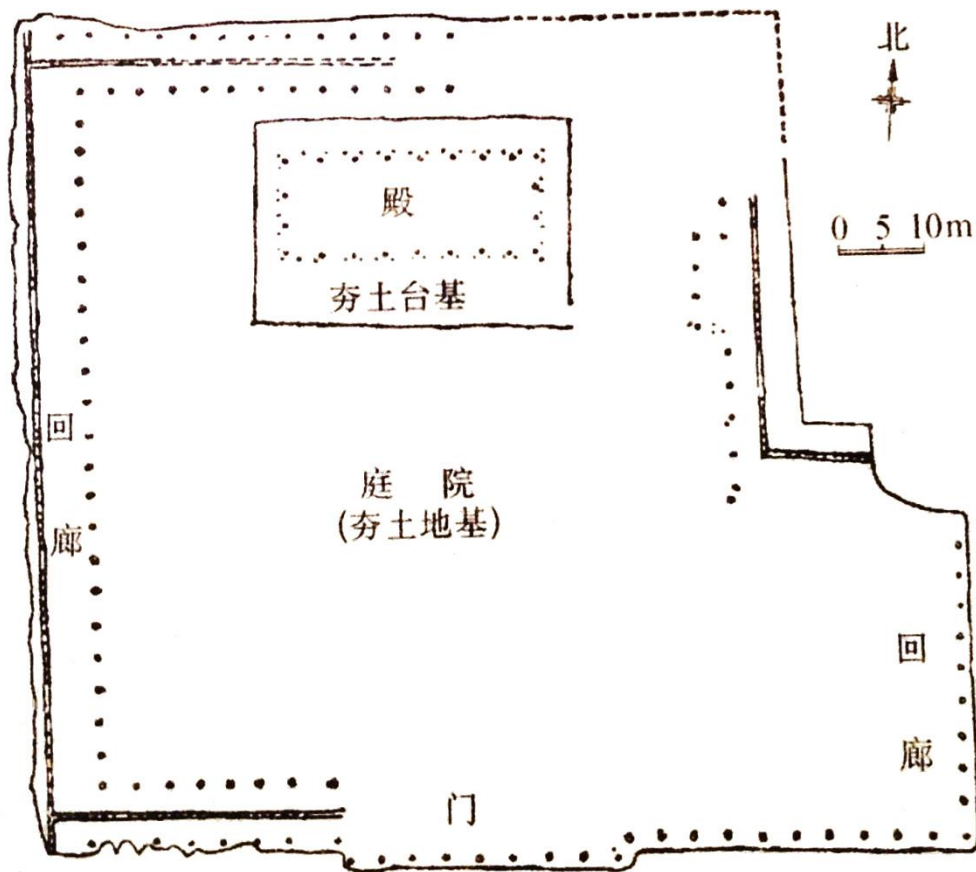


Figure 5. Plan of capital city palace by the end of Xia Dynasty (Pan, 2009, p. 21)

In the Shang Dynasty (1600BC—1046BC), the written language—hieroglyphics first appeared in China. Four examples are shown in Figure 6. In each example, the upper one is the hieroglyphic while the lower one is the currently used language in mainland China—Chinese simplified character. The upper left means “palace”. The upper right means “capital”. The lower left means “room”. The lower right means “house”. The meanings of these hieroglyphics are all closely related to architecture. Together with other relevant hieroglyphics, it is presumed that some buildings had a base at the bottom (Liu, 1984, p. 29). In Henan province Zhengzhou, one historical site has been found and shows that rammed earth technology was highly developed in Shang Dynasty and this technology is a milestone in the ancient period (Liu, 1984, p. 30). This technology is still used now and highly appreciated by the Chinese architect Shu Wang (Pritzker Prize winner in 2012). An example will be given in 1.1.1.3. Another historical site of the palace is found in Henan province Anyang Xiaotun village that the palace consists of many individual buildings built successively (Liu, 1984, p. 31). There is a vertical central axis of the palace plan, with the symmetric layout. Individual buildings are grouped together and functioned as major or minor buildings. This palace style of “public area at the front, private

area at the back, symmetrically planned with vertical central axis” had passed on and deeply influenced all the subsequent dynasties. Apart from the plan, it is found that the diameter of the column base reached 15—30cm which indicates in the Shang Dynasty, the timber frame architecture had reached a very large scale (Liu, 1984, p. 31). Near the palace, sites of houses for slaves are also found. These houses are smaller and rough. This implies that the social class deeply distinguished the architecture at that time and this distinction is further developed in the subsequent dynasties and even clearly defined in the two rulebooks.

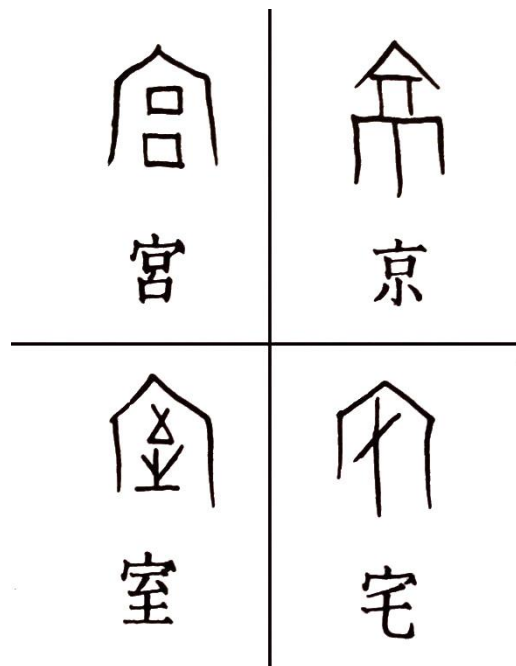


Figure 6. Hieroglyphics in Shang Dynasty (Liu, 1984, p. 30)

The Zhou Dynasty (1046BC—221BC) is a transition from a slave to a feudal society. In this dynasty, the scale of cities, scale of important architecture, width of roads, height of city walls were all distinguished by the social class of the owners. Otherwise it would be treated as breaking the law (Pan, 2009, p. 23). A historical site of a quadrangle courtyard is found in Shanxi Qishan Fengchu village (see Figure 7). From the plan it is obvious that the courtyard is symmetrical around the vertical central axis. This is the earliest and most complete example of the quadrangle courtyard found in China (Pan, 2009, p. 24). Another significant achievement is the use of tile and brick, which leads the architecture from the rough and poor looking to the fine and advanced looking. These two inventions were passed on even until today and the utilisation of such materials gradually becomes one of the key features of the Chinese style. Towards the late Zhou Dynasty (defined as Warring States period, approx. 475BC-221BC), the palace started to be equipped with bathrooms, heating

devices inside living areas and bathrooms, cellar for frozen food, as well as water pipes (Pan, 2009, p. 28), which indicate an advanced level of construction technologies. In the tombs, waterproof layers are found (Pan, 2009, p. 29) and the tenon—mortise connections were developed to a variety of forms and accurately made. And this development is considered as the earliest origin of the *dou gong*.

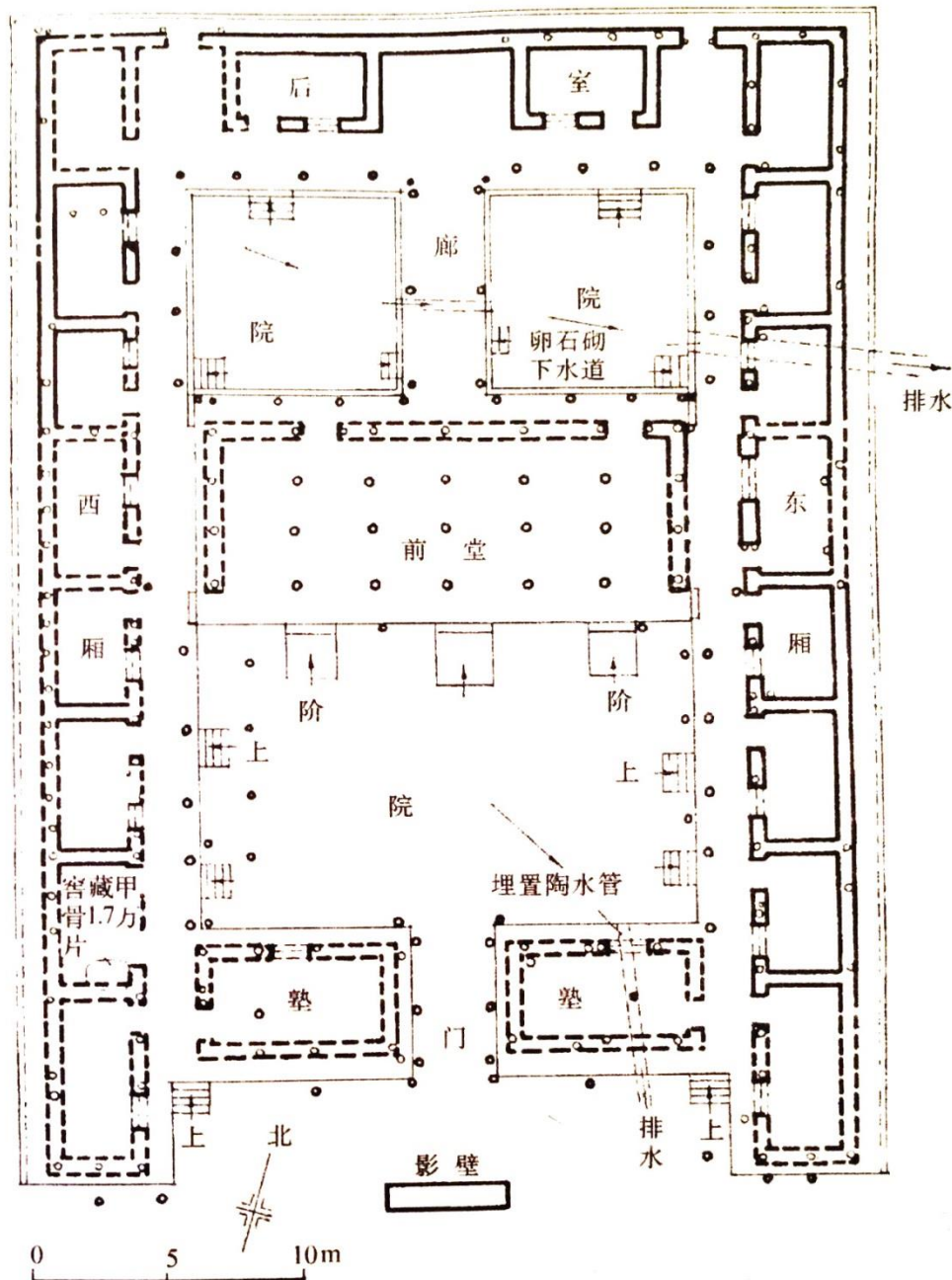


Figure 7. Shanxi Qishan Fengchu village quadrangle courtyard plan (Pan, 2009, p. 25)

The Qin Dynasty (221BC—206BC) is the first feudal dynasty and very short, but some spectacular architecture was built in this dynasty. E'pang Palace was one of the most famous but unfortunately, the Qin Dynasty finished before its completion and it was destroyed in the war shortly after. No archaeological excavation has been done so far (Pan, 2009, p. 30). The historical site of the rammed earth base is more than 1km in width and 0.5km in depth, the remaining height is 7—8m (Liu, 1984, p. 48). Even though, in historical literatures and poetries, it was extremely highly praised by posterity due to its magnificent scale as shown in Figure 8. In *the verse of E'pang Palace* written by the poet Mu Du in Tang Dynasty (618—907), it was described as “...覆压三百余里，隔离天日。...盘盘焉，囷囷焉，蜂房水涡，矗不知乎几千万落。...” which means “...it occupies a length of more than 300 Li (1 Li= 500m), the buildings are as high as that can shade the sky... millions of buildings are spread out spirally upwards the mountain...”. Another famous architecture complex is Mausoleum Qinshihuang Emperor. But the archaeological excavation has not yet been done (Pan, 2009, p. 30) due to technical limitations. According to the current investigation, the size of it is very large and there should be even underground rivers made of mercury, which indicates the advanced technologies used in the Qin Dynasty. And it is believed that the current technology may not properly protect it once excavated. In addition, the Great Wall is also a masterpiece which started to be built in the Warring States period. Until Qin Dynasty, the Great Wall reached over 3000km as a protective system (Pan, 2009, p. 30). In the following thousand years, the subsequent dynasties keep adding and maintaining the Great Wall. The current one existing near Beijing was built in Ming Dynasty (1368—1644). Although this dynasty was short, the inspiration is very important. In Chinese history, wars were very frequent both with surrounding states and within Central Plains when dynasty changes or for other political reasons. Usually the new emperors or winners would destroy the old palaces and temples or even cities, by setting fire to them. Therefore much magnificent architecture could only be found in legend. But those either have the finest design to prevent the damage or have been used by the subsequent dynasties have survived.



Figure 8. Drawing of an impression of the E'pang Palace (Lee, 2014)

The Han Dynasty (206BC—220) was a period of prosperity and one of the foremost dynasties in Chinese history. Its capital city Chang'an (today called Xi'an in Shanxi province) was 2.5 times as large as the city of Rome in 4th century (Pan, 2009, p. 33). The prosperous economy offers the rapid development in architecture. One outstanding aspect is the timber frame structure had achieved a mature level, and multi storied timber frame buildings have appeared. The two widely used typology of *Tai Liang* and *Chuan Dou* in the subsequent dynasties were formed at the time (see Figure 9, the types will be further introduced in Chapter 4) (Pan, 2009, p. 31). And these two types were still used until contemporary period. Another significance is the utilisation of *dou gong* (see Figure 10). Although the forms of *dou gong* at the time were not standardized as in Tang Dynasty (618—907) or Song Dynasty (1125—1279), its structural function was significant that taking the load of the outwardly projecting roof to enable the roof extension. Based on this, the roof shape also had variations and formed one of the key features of Chinese style. Unfortunately no building has survived.



Figure 9. *Tai Liang Type* (up), *Chuan Dou Type* (middle) and *Jing Gan Type* (low) (Liu, 1984, p. 70)

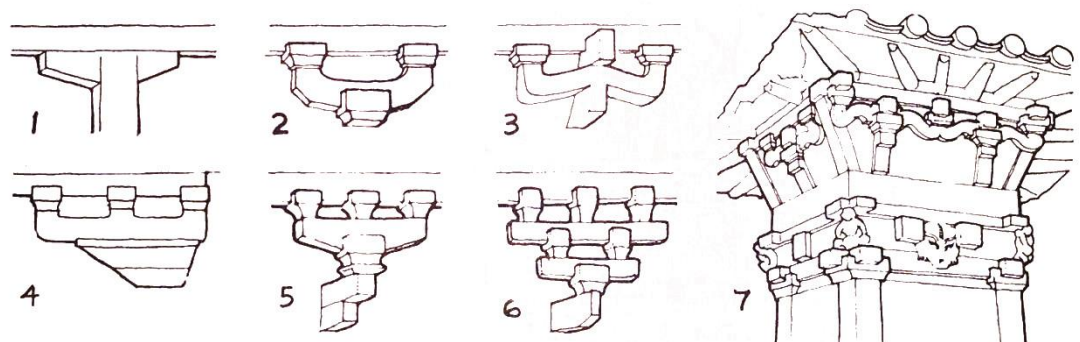


Figure 10. *dou gong* in Han Dynasty (Liu, 1984, p. 75)

From 220 to 589, the Chinese history experienced Three Kingdoms, the Jin Dynasty, as well as the South and North Dynasty. It was an age of turbulence with serious destruction by continuous wars. The country kept dividing into states for a long period. Thus innovation in architectural technology stalled and was mainly inherited from the Han Dynasty. But meanwhile, with the introduction of Buddhism from India, pagoda and grotto (cave) were introduced into China at the period (Pan, 2009, p. 34). With the integration of Chinese timber frame structure into the construction of pagoda and grotto, the Chinese pagoda (especially multi storied pagoda) and grotto appeared and was highly developed during this period. The Dunhuang Mogao Caves in Gansu province is one of the most famous. From Figure 11 and Figure 12, the wooden building constructed in front of the caves of the Buddhist sculpture.



Figure 11. Dunhuang Mogao Caves elevation photo (Anon., 2015)



Figure 12. Dunhuang Mogao Caves section image (Anon., 2015)

After the long division period, the Sui Dynasty (581—618) was built up. Since then, the Chinese history entered the second highly developed period and reached the peak in Tang Dynasty (618—907). In Sui Dynasty, the Beijing-Hangzhou Grand Canal of 1800 km was completed, which was the world's longest manmade waterway and effectively connected the north and south part of China, allowing the exchange of both materials and culture. The Grand Canal continued in use in the subsequent dynasties. The second contribution was the construction of the two capitals—Daxing City (west capital, called Chang'an before and after the Sui Dynasty, called Xi'an today) by architect Kai Yuwen and Luoyang City (east capital). Both cities were spectacular and planned almost perfectly. Since the Tang Dynasty inherited both capital cities, they will be described shortly. Another famous project was the Anji Bridge (also named Zhaozhou Bridge) in Hebei province Zhao town by architect Chun Li (see Figure 13) (Pan, 2009, p. 38). The span of the arch reached 37m with the four minor arches at both sides to reduce the net weight and reduce the water flow impact pressure in flooding. It has been preserved and still in use due to its great anti-earthquake resistance. For an ancient period, it displays an essence in Chinese style that using the natural material with the sophisticated structure and connection design to achieve anti-earthquake aim. The Chinese joint *dou gong* is the best exemplar of this.



Figure 13. Hebei province Zhao town Anji Bridge (Anon., 2013)

Following this, during the Tang Dynasty (618—907), technology, culture and economics developed rapidly. This is another prosperous period and foremost dynasty after Han Dynasty. Thus the architecture development had also reached a new level. Firstly, the city planning achieved a high level. The west capital city Chang'an was inherited from Sui Dynasty. It was the largest and most cosmopolitan city in the world, with a population which at the height of Tang glory in the first half of the eighth century exceeded one million (Fu, et al., 1984, p. 92). The imperial palace Daming Palace was three times as large as the extant Forbidden City even excluded the lake area (Pan, 2009, p. 39). The great outer walls of the capital enclosed an area of 84 km, divided into an outer city, imperial city and palace city. Broad avenues, 14 north-south and 11 east-west crisscrossed the outer city, forming 110 separate wall-enclosed sectors (see Figure 14). This symmetric rectangular plan with regular inner divisions is a significant feature not only in city planning, but also in the floor plan of individual buildings. These features also highly impacted on several cities in Japan and Korea such as Heijokyo (an old capital city in Japan) with almost the same plan but smaller scale. Secondly, the timber frame structure achieved an even more advanced level. The individual buildings such as Daming Palace Linde Hall had a size of 5000 m² using 11 bays to constitute the total building width (definitions see Chapter 3) (Pan, 2009, p. 39). Even, the form and material of *dou gong* were standardized. In Tang Dynasty, “the rule of material” first appeared. In other words, the utilisation of the wood material in structural parts was standardized such that based on the section size of the wood to calculate the quantity of the material and catalogue different sizes of wood. In this way different parts could be manufactured at the same time and assembled later to shorten the

construction period. This is the foundation of “the rule of eight grades of standard timber material (called *Cai*)” in the Song Dynasty recorded in *Ying Zao Fa Shi* (this concept will be introduced in Chapter 2, Chapter 3, and Chapter 5). In general, the architecture in the Tang Dynasty had both functional and aesthetic features, appearing grave and magnificent, which was the basis of the subsequent dynasties and also deeply impact other Asian countries. Therefore it is also called the Tang Style and recently developed to a New Tang Style.

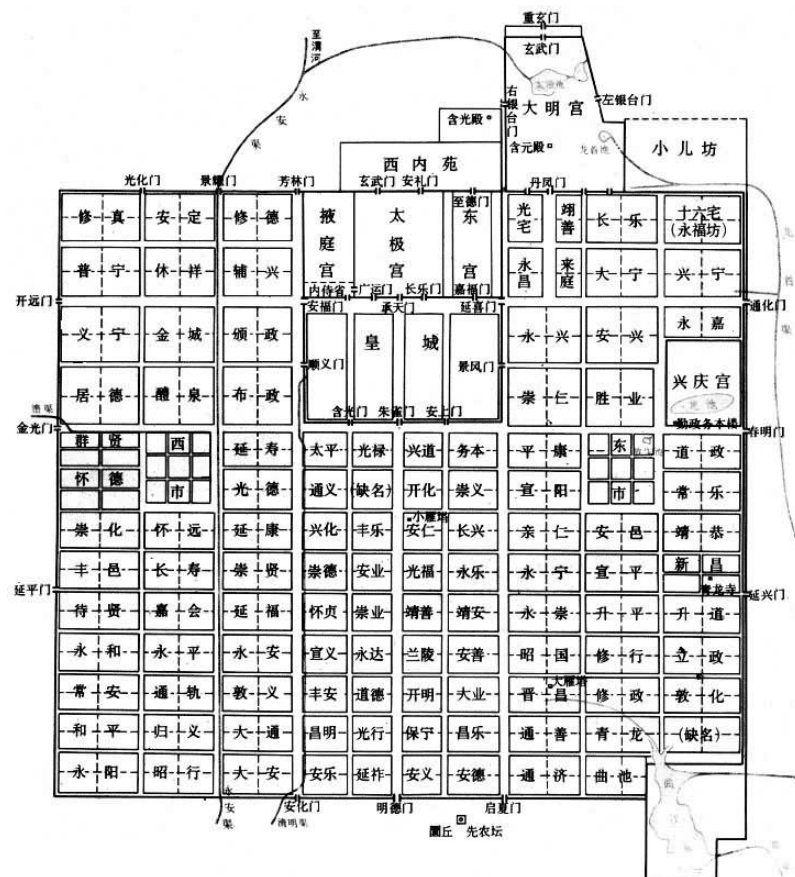


Figure 14. Tang Dynasty capital city Chang'an (Liu, 1984, p. 118)

During 907—960 it was the Five Dynasty and Ten Kingdoms period which the country was divided into states again with continuous wars. Architect Hao Yu wrote *Mu Jing* (Carpentry Principle) but unfortunately this book has been lost.

Since 960, the Song Dynasty (960—1279) built up and unified most parts of the nation. The Song Dynasty was weak in politics and military but technology and economy developed rapidly, especially in south China. This also changed the general architecture style from the magnificent large scale in Tang Dynasty to a more

sophisticated and smaller scale. There were several well-known aspects. Firstly, the city planning has changed due to the lifestyle of people and function of the city. In Tang Dynasty, people were kept within sectors (the small rectangles in Figure 14) and not allowed to go out in night time. However, the capital city Bianliang in Song Dynasty was a prosperous business city, so streets, shops, bridges and public transportation systems were highly developed. Figure 15 is the famous painting *Qing Ming Shang He Tu* (Along the river during the Qingming Festival) drawn by artist Zeduan Zhang in the Song Dynasty (displayed in three sections due to its length). This 5.5m long scroll depicts for the first time residents' everyday life and detailed architecture. From this painting the characters of city and architecture in Song Dynasty can be clearly seen. For example, Figure 16 shows the roof, columns and *dou gong* of the building on top of the gate. Secondly, the rulebook *Ying Zao Fa Shi* compiled by Jie Li in 1103 was a milestone in Chinese architectural history. This is the existing earliest official architecture literature in China. The book summarized methods, skills, techniques, experiences from builders and carpenters in all previous dynasties and made a guideline officially. The spirit of this book is “the rule of material” such that setting “the rule of eight grades of standard timber material (called *Cai*)” as a standard to distinguish building levels. Once the level of the building (based on the owner's social class or the function of the building) is confirmed, the grade of the standard timber material is then determined. Then the whole set of the components of the timber structure is also determined based on these rules. Therefore, the design period is shortened, the estimation of material is standardized and the construction is progressed more quickly. As mentioned in the last paragraph, this rule may already be implemented in Tang Dynasty or even earlier, but this book is the first written evidence and upgrades the rule to the official level. This rule also has a huge influence on all the subsequent dynasties and has been followed ever since. Thirdly, the scale of individual buildings became larger and the roof part became more complicated which indicated the construction technology had achieved a new level. The Yellow Crane Tower in Hubei province Wuhan city shown in Figure 17 is an example. In general, by the Song Dynasty, the traditional Chinese architecture has experienced rapid development and innovation, and achieved a mature level with a unique Chinese style.

Meanwhile, since 907 to 1227, three dynasties built by minorities in the north part of China existed in parallel with Song Dynasty, which were Liao Dynasty (907—1125), Jin Dynasty (1115—1234) and Xixia Dynasty (1032—1227). Several temples and pagodas were left until today and they become important examples for current research (examples will be used in Chapter 3).



Figure 15. *Qing Ming Shang He Tu* (Along the river during the Qingming Festival) (Zhang, n.d.)

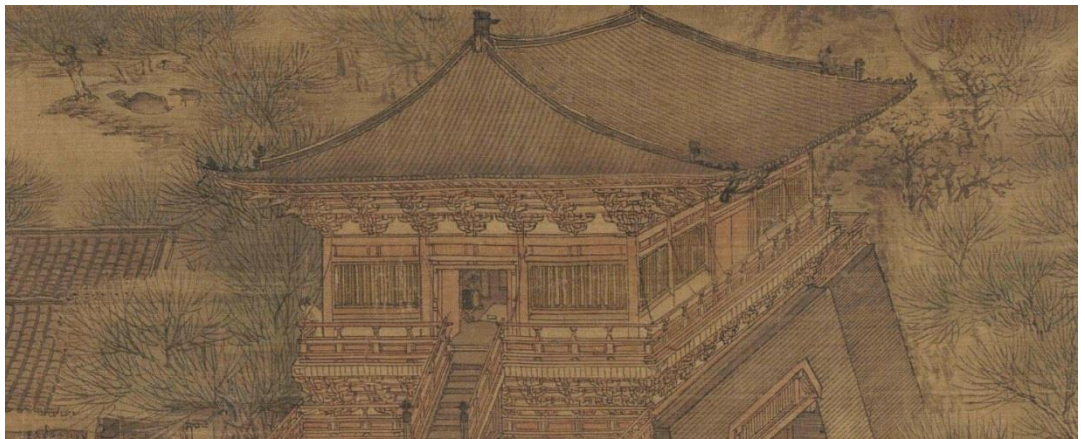


Figure 16. Part of *Qing Ming Shang He Tu* (in red box of Figure 15) (Zhang, n.d.)



Figure 17. Yellow Crane Tower

The Yuan Dynasty (1279—1368) was built by minority of Mongolians. Due to the wars and brutality in politics, it was a barrier to cultural and economic development. Therefore, architectural innovation also stopped but was mainly inherited from the Song Dynasty. Nevertheless, compared with those in the Song Dynasty, the timber frame architecture in the Yuan Dynasty had a smaller scale and worse quality, with rough manufacture and inaccurate material quantities. In addition, some components were removed or simplified, such as *dou gong* and column. This was due to the economic difficulty and a shortage of timber. As a consequence, the character was different from the Tang and Song dynasties, which became simpler. But sometimes serious problems also appeared such as the commonly used method “reducing the number of the columns” in the Yuan Dynasty. Figure 18 shows section and plan of Guangsheng Temple Lower Monastery Main Hall in Shanxi province Hongdong. In original design, there were only four main columns inside the hall in each row, which

reduced six columns in each row (Pan, 2009, p. 47). In the plan, the two columns in red boxes were added later because the four original columns in each row could not take the heavy load due to the large span. This is a typical failure example indicating that the components in timber frame architecture cannot be reduced arbitrarily. On the other hand, the capital city of Yuan Dynasty was built in Beijing, and this was a foundation for the later prosperity of Beijing in the next two dynasties.

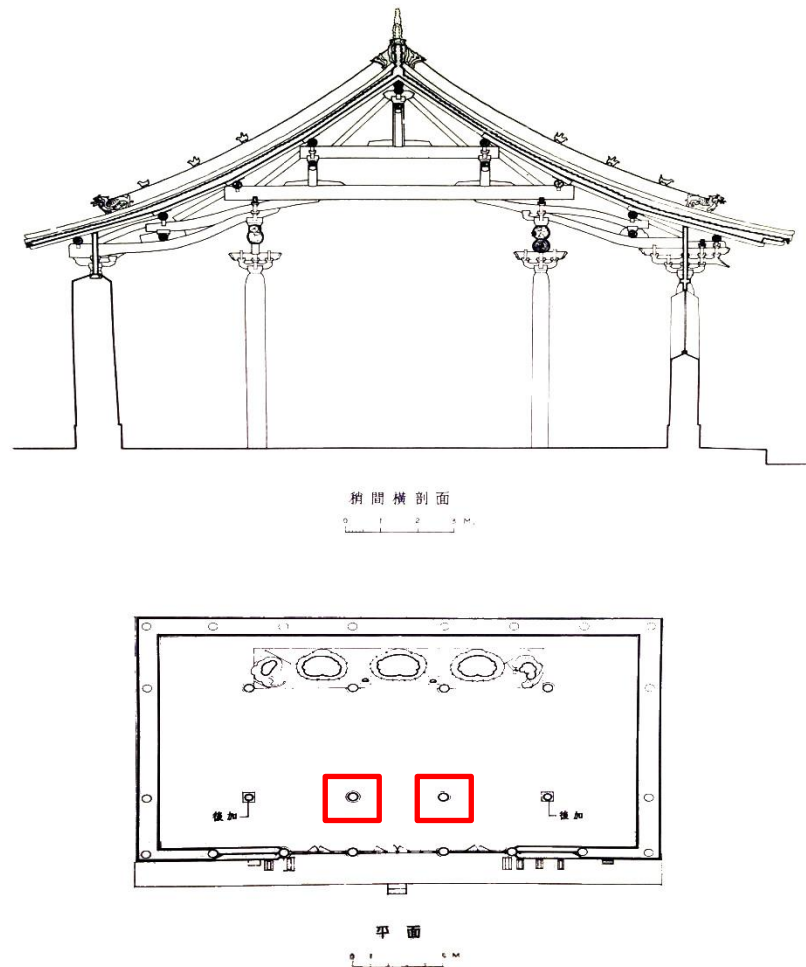


Figure 18. Section and plan of Guangsheng Temple Lower Monastery Main Hall (Liu, 1984, p. 273)

The Ming Dynasty (1368—1644) first chose Nanjing as its capital but fairly quickly moved to Beijing. Today's Forbidden City has been built since Ming Dynasty and passed on to the Qing Dynasty (1636—1911) to continue to be used as imperial palace. This will be introduced further in the next paragraph. Until the Ming Dynasty, the brick technology was highly developed to an advanced level so bricks were widely used in walls of the buildings. Before the Yuan Dynasty, although bricks had been used for towers and tombs, rammed earth walls were used in the majority of

timber frame architecture (Pan, 2009, p. 48). Since brick walls performed better than rammed earth walls in wet weather conditions, the outwards overhang of the roof could be reduced. Therefore, the structural function of *dou gong* was largely reduced as well. However, since the palaces and temples still pursued a luxurious and gorgeous exterior, *dou gong* did not disappear completely but changed to a more complicated and attractive form to mainly fulfil the aesthetic function. And this phenomenon was also continued to the Qing Dynasty. Meanwhile, the method of “reducing the number of the columns” in the Yuan Dynasty stopped in palace and temple constructions. So the large scale official architecture in Ming Dynasty was rigorous. Another benefit from the brick technology was the expansion of the Great Wall. The Great Wall constructed in Ming Dynasty of 8851.8 km consisted with mainly bricks (Li, 2009), and those left until today were mainly built in that period (see Figure 19). Apart from these, the Chinese style gardens became popular since then, especially in south China. The Humble Administrator's Garden (see Figure 20) and The Lingering Garden (see Figure 21) are two famous examples in Jiangsu province Suzhou city remaining today. This was a foundation of the imperial gardens built in Qing Dynasty. Meanwhile, the book *Yuan Ye* (Craft of Gardens) written by Cheng Ji in 1631 described many garden designs. This book is currently famous internationally and has been translated into English and French (Hardie, 1988) (Chiu, 1997). In addition, the concept of *feng shui* (wind and water) was extremely advocated in Ming Dynasty, and this deeply impacted on many aspects regarding architecture, such as the location and orientation of the buildings, or the space arrangement of the courtyards, both for imperial and civic architecture.



Figure 19. The Great Wall constructed in Ming Dynasty (Li, 2009)



Figure 20. The Humble Administrator's Garden



Figure 21. The Lingering Garden

The architecture in the Qing Dynasty (1636—1911) mainly inherited from the Ming Dynasty and based on that further developed. Firstly, the gardens reached a prosperous period that many imperial gardens were masterpieces, such as the Yuanming Palace (although destroyed in the Opium war in 1860) and Summer Palace in Beijing. Secondly, since the Qing Dynasty was also built by the minority of Manchu, the ethnic fusion was obvious and various types of architecture have been developed depending on natural environment and cultural tradition in different regions. Figure 22 is the Potala Palace in Tibet which mixes the Tibetan and traditional Chinese style together (Pan, 2009, p. 51). Figure 23 is the Hakka Tulou (group houses) in Fujian province which mixes the rammed earth wall externally and an inner timber frame structure. Figure 24 is the traditional Beijing quadrangle courtyard which is a symmetric rectangle with a central axis. Thirdly, the Forbidden City (see Figure 25) was the Imperial palace from the Ming Dynasty until the end of the Qing Dynasty. The complex consisted of 800 buildings with 8,886 rooms and covered 720,000 square metres (Bao, n.d.). It was declared as a World Heritage Site in 1987 as the "Imperial Palace of the Ming and Qing Dynasties" and was listed by UNESCO as the largest collection of preserved ancient wooden structures in the world. Fourthly, the rulebook *Gongcheng Zuofa Zeli* (also spells as *Kung-ch'eng tso-fa tse-le* in the past, means Structural Regulations) compiled by the Ministry of Public Works of Qing Dynasty in 1734 was the second milestone in Chinese architectural history. Together with *Ying Zao Fa Shi*, they are known as the “two text books of Chinese ancient architecture” (Liang, 1985, pp. 1-16). They are the only remaining classical official Chinese literature which deals with architecture and are, in essence, rulebooks that govern most aspects of the design. Fifthly, based on “the rule of eight grades of standard timber material (called *Cai*)” in Song Dynasty, Qing Dynasty changed this rule to “set the length of *dou kou* (definition see Figure 62) as a standard length to determine all the other components of timber structure”. Once the standard length of *dou kou* was confirmed, the dimensions of the building and timber materials were then determined. Therefore, the time of design and construction would be both shortened and more time could be spent on the interior and decoration. This change is believed that in some cases even simpler than the rule in the Song Dynasty. Lastly, the Lei family, spanning eight generations, was an influential and respectable group in the long history of Chinese architecture. During a period of over 200 years (1683—1890) during the Qing Dynasty, they took the position of “Royal Chief Architect” not by succession, but by competition. Almost all royal architecture at that time, including the Forbidden City (maintenance and refurbishment), the Yuanming Palace, the Summer Palace, as well as the Eastern and the Western Royal Tombs of the Qing Dynasty were designed by the Lei family. Of the two main distinguished contributions by the Lei family, one was their magnificent architecture, and the other was “the Portfolio of The Leis”, including diagrams, models and instructions. Figure 26 and Figure 27 are two examples from the Portfolio of the Leis. These are the very precious research material.



Figure 22. Potala Palace in Tibet

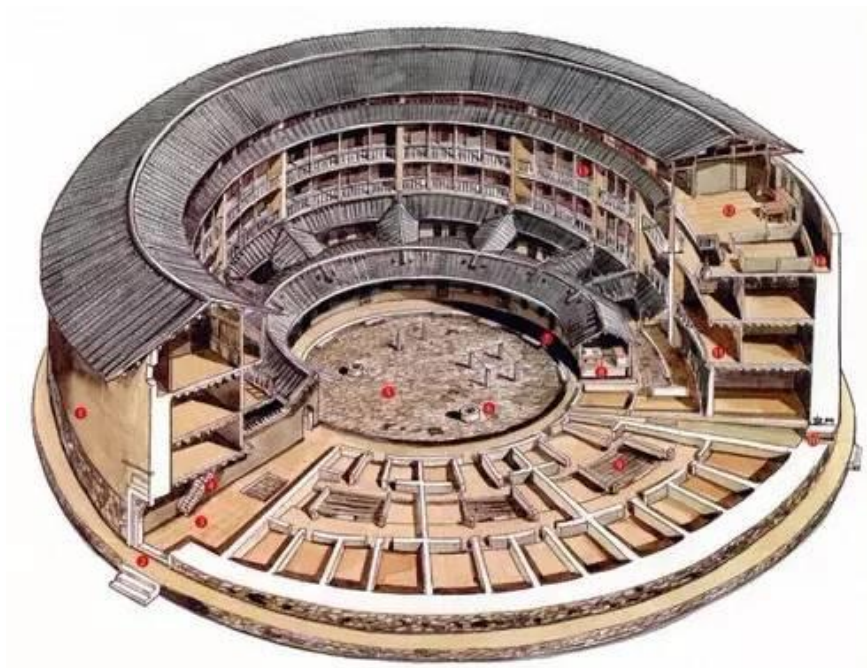


Figure 23. Hakka Tulou (Group Houses) in Fujian province (Anon., 2015)

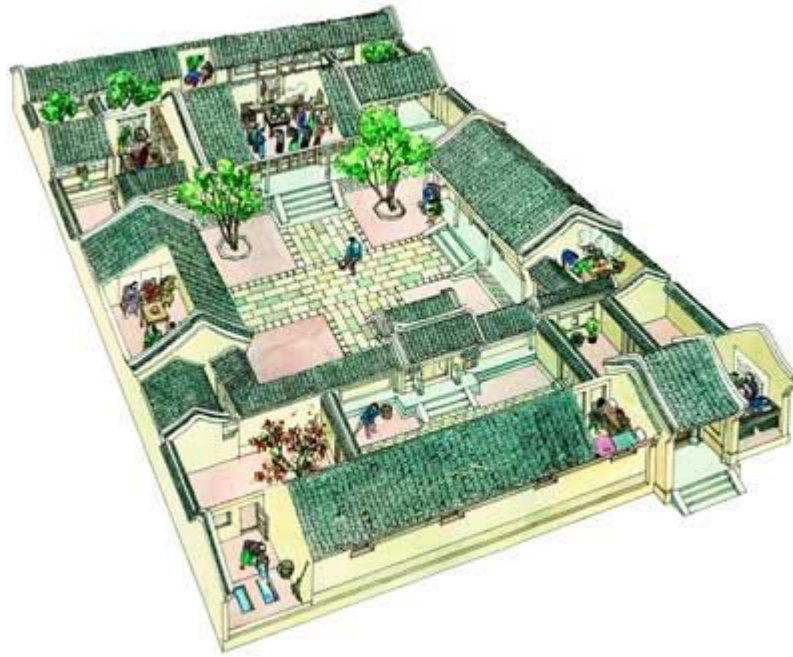


Figure 24. Beijing quadrangle courtyard (Wang, 2009)



Figure 25. The bird's eye view of the Forbidden City (Shi, 2015)

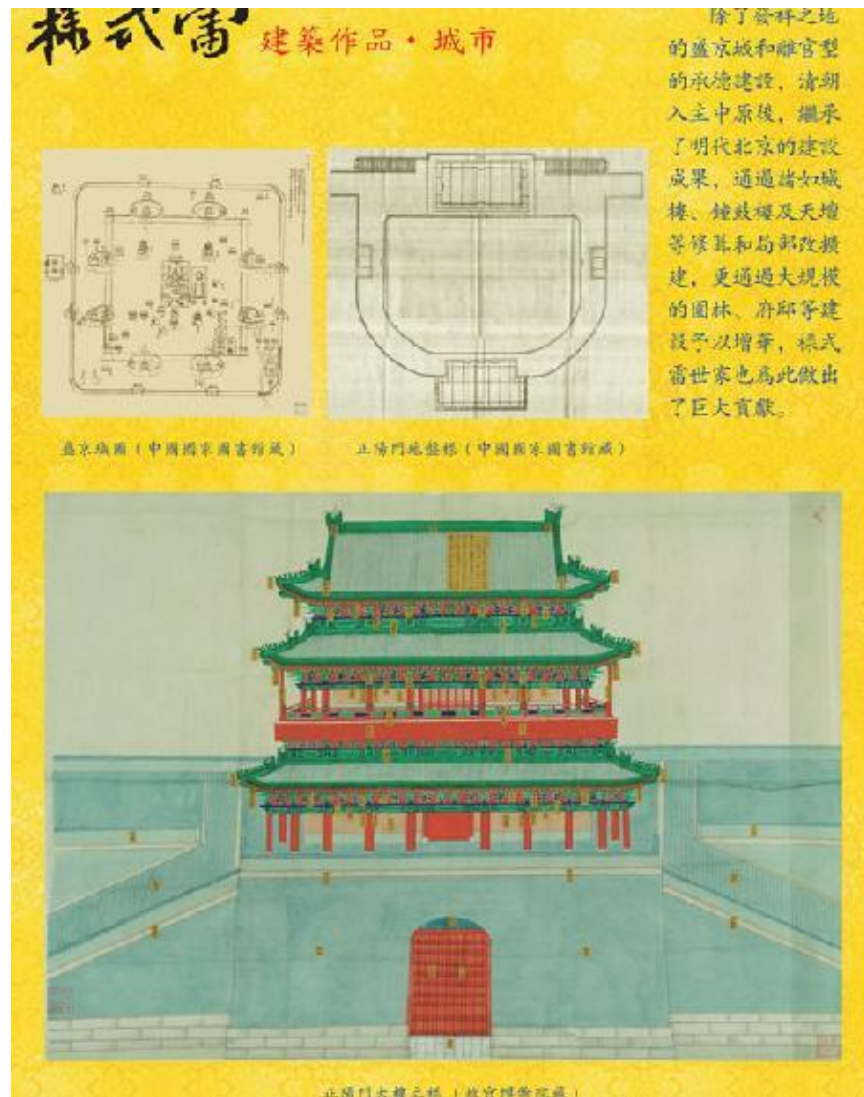


Figure 26. Diagram of the Portfolio of the Leis (Guo, 2010)



Figure 27. Model of the Portfolio of the Leis (Anon., 2014)

1.1.1.2 Current status of research

To discuss traditional Chinese architecture, two references are essential—extant buildings and literary records. It is regrettable that both aspects are so limited.

As mentioned above, timber has a relatively limited life since it is easily degraded and damaged in natural environment as advanced chemical protection was not available in ancient periods. So unlike those made with stones or other strong materials in other countries, timber frame architecture has this natural disadvantage in surviving the passage of time. This is the first reason that many historical masterpieces are lost.

Another reason is, many palaces, temples and cities that the emperors spared no effort to build are easily destroyed by other people, such as in the war or by improper political decisions. Even the civic houses may be destroyed mainly by the natural environment; these great landmarks are destroyed primarily by human activities.

In early ancient periods in China, there was either none or very limited written language to record building technology. Later, although highly civilized language has been used, the design and construction technologies and skills were common knowledge only among the builders. Usually these builders, even the chief builders, were of a very low social class. So most of them did not have sufficient education to read or write. Even though some of them did write records, they were not included into the official records and so were easily lost to history. The two existing rulebooks mentioned above are both officially published, but they are actually one out of thousands. And in fact, very few names of the builders (who are called architects in the early section) or their architectural legacy, are recognised until recently.

The study of Chinese architectural history and documents did not begin until 1901 (Fu, et al., 1984, p. 50). This has been done firstly when a commission of Japanese architects photographed, measured, and described the Forbidden City in Beijing. They reported on the existing buildings and cited the Chinese sources of the buildings and their dates of restoration (Ito, 1903). Early Western scholars on this subject did not rely on Chinese texts. European historians of Chinese architecture such as Gisbert Combaz and Ernst Boerschmann limited their works to photographs, descriptions and roughly measured drawings of plans and cross-sections (Fu, et al., 1984). They were mainly interested in those structures unique to China, such as pagodas, city walls, or towers, and such details as the exotic lattice work in temple or palace halls (Gisbert, 1907) (Boerschmann, 1911). They did not make any attempt to establish any sequence of historical change. Chinese architecture was regarded as static, by both Western and Chinese scholars (Fu, et al., 1984). But this opinion is actually not true, as described in the last section and will be further discussed later. In 1929, Qiqian Zhu and a group of Chinese scholars interested in the *Ying Zao Fa Shi* established the society for Research in Chinese Architecture (*Zhongguo Yingzao Xueshe*). Sicheng Liang joined in 1931 and he did huge amount of important work

into the investigation of ancient Chinese architecture and two rulebooks, and made huge advances in this area. His work (which will be discussed in detail in 2.2) is one of the most important basis for the later research on this subject, and for this thesis as well. But to unfold the secrets of the rulebooks, problems still exist. A great number of technical terms written in an ancient language make the books hard to understand by today's researchers, therefore there are many obscure meanings awaiting further investigation.

In recent years, a completed version of the original *Ying Zao Fa Shi* has been republished based on the collections from all kinds of sources over a long time. This book (Li, 2006) keeps all the contents and language as its origin of the second edition published in 1103 (Li, 1103). Then a more recent version with punctuation added into the ancient language has been published as a step of progress (Zou, 2011). After this, a translation from ancient language to modern language has been published for a clearer understanding of the content (Wang, 2013). Apart from these, architectural historians also study the scale and proportion of timber frame ancient architecture (Wang, et al., 2011), as well as the carpentry technology (Ma, 2003). In addition, a project of research on the Yuanming Palace has been taken by Tsinghua University since 2000 to 2012 (Guo & He, 2012). Similar influential publications and projects continue to be researched.

However, several limitations still exist. Firstly, some of the research on architectural history is very general mainly in the form of narrative description, but lacking a deeper understanding of the technical and detailed terms. Therefore those unrecorded and lost contents cannot be interpreted. This leads to many traditional skills which cannot be passed on. Secondly, for some recorded terms in the rulebooks, different scholars may have different interpretations, due to the difficulty of the ancient language and lack of enough extant building examples. These increase the debatable issues but are of little help in finding out evidence. Thirdly, individual research projects are mainly focussed on individual issues, but there is a lack of interconnections to review the Chinese style as a whole. Thus, the Chinese style remains fragmented. But in reality it has developed continuously. Fourthly, the majority of the research publications are written in Chinese, which limits the international impact in the area. In many architectural history textbooks and taught modules, Indian and Japanese architecture are included with good documentation but Chinese architecture is not. To sum up, there is a lack of systematic and complete records to date.

In recent years, Andrew Li's work of applying shape grammar to the architectural style of the *Ying Zao Fa Shi* is internationally well known and contributes to both CAD and Chinese architecture fields. He emphasizes the novel technical challenges the rulebook presents: text as a primary source, combinations of symbolic description and drawings, and the incompleteness (to modern readers) of the text. In his research, a systematic approach is taken to characterize Jie Li's principles in a grammar. More details and other relevant research will be discussed in 2.5.4.

1.1.1.3 Current status in urban planning and architectural design

How to demonstrate Chinese style and show identity through the architecture is a big concept that every local architect, planner and politician should be carefully considered. This has been highly debatable for several decades since the P.R.China has been built up. But a lack of attention and value judgement on the traditional style architecture has been always obvious and the word demolition appears frequently in the news. One typical example is the demolition of the old city gates and city walls of Beijing which began in 1950. The old city wall system was first built up in 1553, consisted of 16 city gates and nearly 40 km city walls (see Figure 28). Figure 29 shows different city shapes of Beijing as capital in different dynasties. According to the early sections, city walls and gates played a significant role in all dynasties and could be a symbol of the capital city. The famous architect Sicheng Liang had a proposal (see Figure 30) of the utilisation of the old city walls to both protect the heritage and use it in a novel way: On top of the city walls, the average width reaches 10m so that these areas could be used as gardens for a capacity of 10000 people. The city gates could be used as public libraries, museums or tea rooms next to the gardens. The moat river circled outside the city walls would allow citizens to have boating in summer and go skating in winter. If this was true, it would be the only unique three dimensional ring garden of the city of 39.75 km in the world (Anon., 2013). Unfortunately, not only has this proposal has been refuted, but also the old city walls and gates of Beijing have been completely demolished, together with the moat river. Since 2004, six demolished city gates were planned to be rebuilt, but a variety of difficulties were encountered such as the incomplete understanding of the original design, losing of the traditional constructional skills, and doubt about the original materials. Another typical example is the “unimportant” *Hutong* demolition during Olympics planning. *Hutong*, which means alley, consists by courtyard type houses on both sides and indicates the neighbourhood tradition in Beijing (see Figure 31). But to accelerate the preparation of the Beijing 2008 Olympic Games, many streets and hundreds of courtyard houses have been demolished (Yardley, 2006).



Figure 28. Old city gate and city wall of Beijing (Anon., 2014)

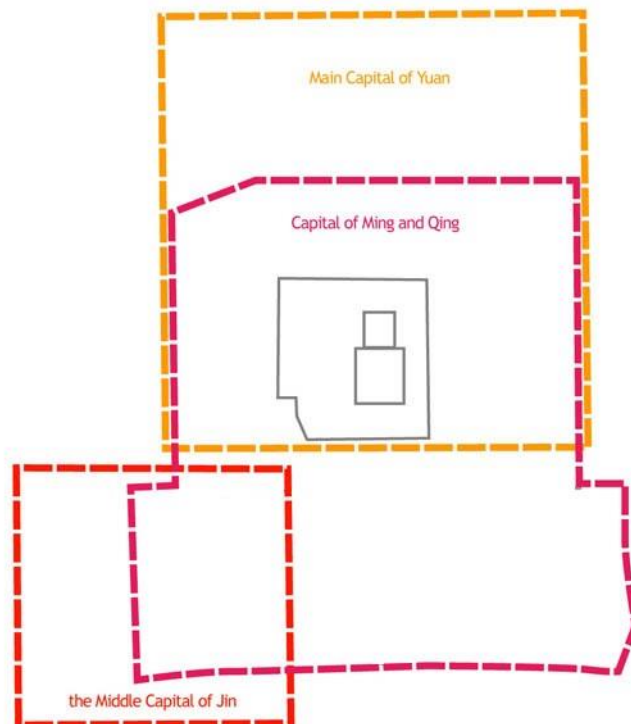


Figure 29. Different city shapes of Beijing as capital in different dynasties

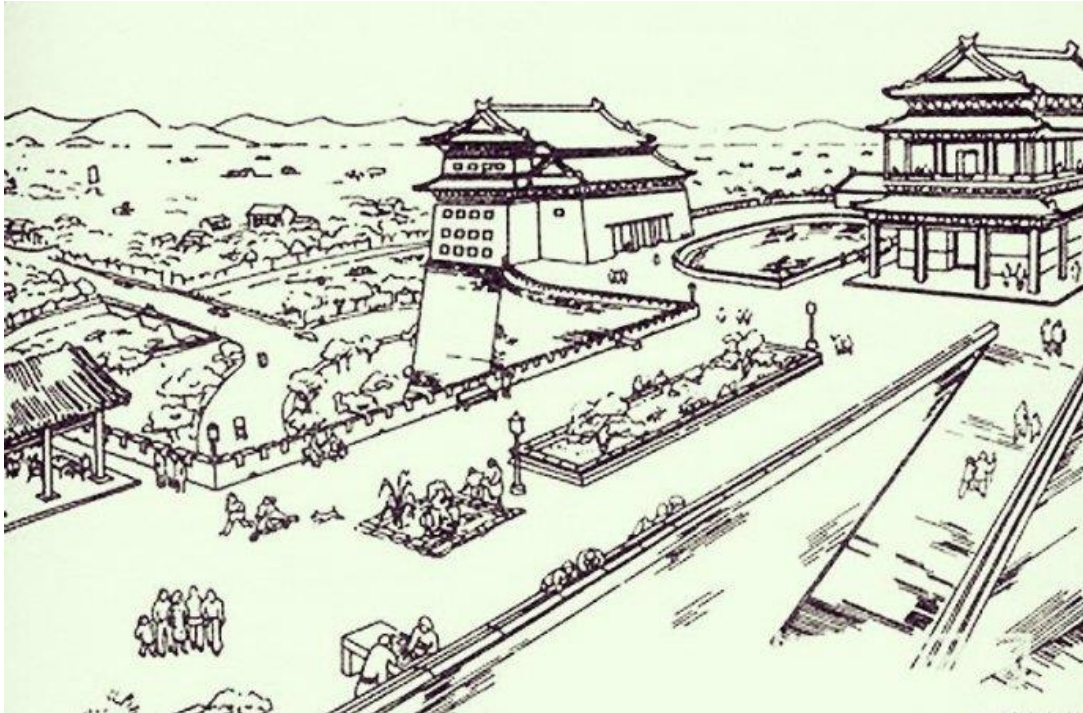


Figure 30. Sicheng Liang's proposal of Beijing city walls (Anon., 2013)



Figure 31. Hutong in Beijing (Carollin, 2014)

In addition to the demolition, fresh attempts that try to follow the modern style are also made in recent years but the results are strongly questionable. A notable example is Hutong Bubble 32 project done by MAD studio in 2006 (see Figure 32 and Figure 33). It mainly concentrates on upgrading the living condition by inserting small elements rather than large scale demolition and rebuilding. For this aim, the attempt of building silver, mirrored bubble as toilet and stairs is quite modern and pioneering, also solving the problem of the poor standard of hygiene—no private toilet inside traditional courtyard. But on the other hand residents, especially older

generation, think it does not match the traditional style according to its structure and appearance. Therefore, except for the function, consideration of harmony and coherence of the surrounding style should also be made. The added bubble seems an alien intrusion which cannot be well integrated into a group of houses. So this becomes a challenging idea to be fully accepted by local residents although this project has won several international awards. And interestingly, considering most western architects and valid architectural criticism tend to think this is very successful, local media praises it with the words “attractive and brings new vitality” (Baidu, n.d.). But indeed this praise is ambiguous without mentioning its specific good points in inheriting tradition. If interviews are conducted with local architects individually, a number of them give the opinion quite similar as local residents and the author. Overall, this has been a valuable experiment to figure out a method of renovation of the traditional houses.

Apart from this, MAD studio also designed the Shan-shui City project (see Figure 34) for Guiyang City. This design is inspired by the Chinese bonsai. The concept of attempting parametric method to renovate traditional culture is worthy of recognition. But this design does not trace back to the real tradition. For example, the Chinese bonsai usually largely scales down the landscape scenery in order to allow the audience to view the whole scenery at one glance and feel the conception. But to do it oppositely, the appreciation to the sophisticated scenery is lost. This is why local people express it as frightening.

Despite this, if the Hutong Bubble 32 project is a pioneering attempt, the National Centre for the Performing Arts is a good architecture placed in a wrong location, as shown in Figure 35. On the way of pursuing modernization, this is not a successful example in local people’s mind. What is even worse, the copycat culture makes the Chinese style lost more seriously but local developers irrationally copy the western style. Figure 36 shows the fake Eiffel Tower and French town in Zhejiang province Hangzhou city. But this town is not well accepted by local people. When it started to be built, the planned capacity was for a 10000 people community. But even until now, most units are still empty so some local media calls it an empty town (Anon., 2013). Apart from this, the replica includes Big Ben, Sydney Opera House, Tower Bridge, Tudor village (see Figure 37), Venice (see Figure 38) and much more. Figure 39 summarises the replica architecture in China. During the developing process, learning or borrowing from others could be a valid method. Nevertheless, the improper replica architecture indicates that there is a lack of self-confidence and cultural identity. Therefore, the “Renaissance of traditional Chinese style” is necessary.



Figure 32. Hutong Bubble 32 project made by MAD Studio (Anon., 2009)



Figure 33. Bird view of Hutong Bubble 32 project (MAD Studio , 2006)



Figure 34. Shan-shui City (MAD Studio, 2012)



Figure 35. National Centre for the Performing Arts (Yang, 2013)



Figure 36. The fake Eiffel Tower and French town in Zhejiang province Hangzhou city (Anon., 2013)



Figure 37. Replica: Thames Town, located 19 miles from Shanghai in China (Preece, 2012)



Figure 38. China's duplicate version of Venice in Dalian city (Victor, 2014)



Figure 39. Fake architecture in China

Based on this idea, architects and developers also started the inheritance of traditional Chinese style. Take the Beijing Cathay View Courtyard Residence project as an example. This project consists of 340 villas and a park, which inspired by the traditional Beijing courtyard house, *Hutong* and imperial gardens (Anon., 2010). As shown in Figure 40, from its rendering effect of the showroom, it looks like traditional Chinese style. But if the floor plans are taken into consideration, problems arise. Figure 41 shows floor plans of the showroom while Figure 42 shows a typical floor plan of Beijing courtyard house. The traditional courtyard house is axisymmetric and clearly lay out the different functions of spaces by the grids of the

arrangement. But the showroom floor plans do not reflect this key feature at all. Meanwhile, the facade shows windows placed on the gable walls, which is contrary to tradition. These multi-storey buildings are also built with concrete walls and reinforced concrete columns rather than traditional timber frame structure and rammed earth or brick walls. So, although the developers promote that the buildings combine the modern constructional methods, technologies and equipments, as well as traditional features recorded in *Gongcheng Zuofa Zeli* (the rulebook in Qing Dynasty) (Zhang & Sun, 2011), they are not. Therefore, this project is merely an applied skin of the traditional Chinese style, but lacking its heart and soul.



Figure 40. Perspective rendering effect of the showroom of Beijing Cathay View Courtyard Residence project (Zhang & Sun, 2011)

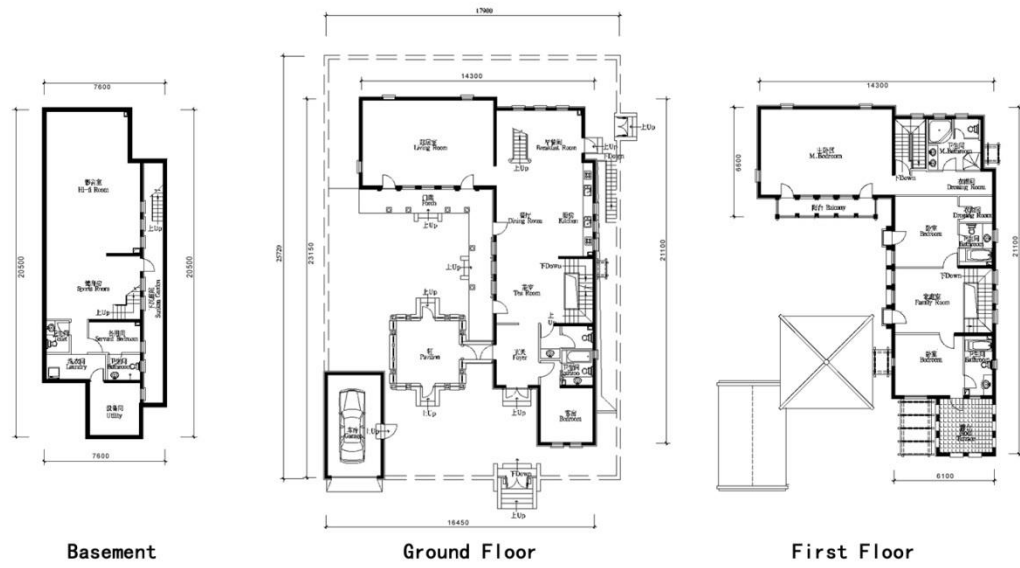


Figure 41. Floor plans of the showroom (Zhang & Sun, 2011)

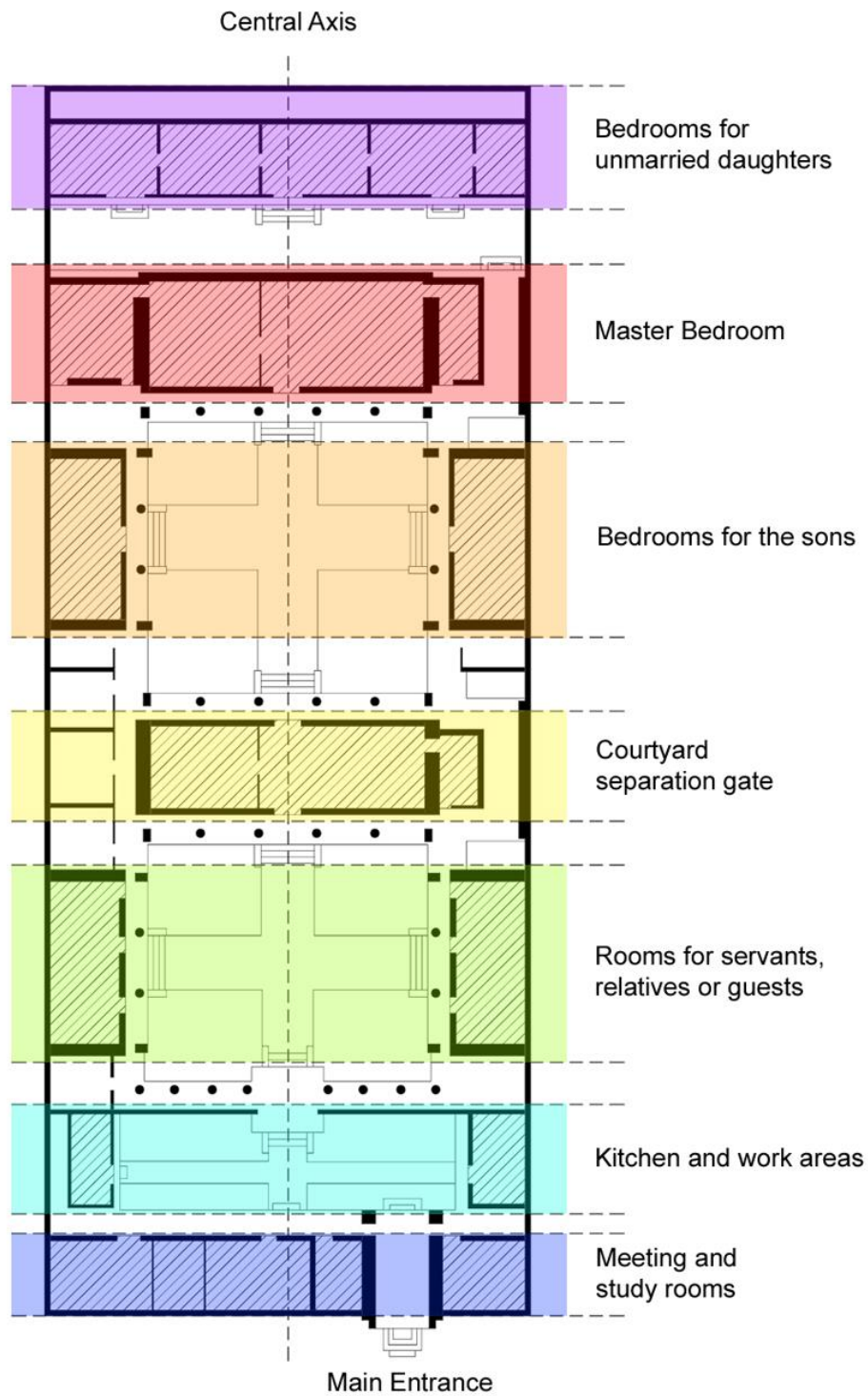


Figure 42. Typical floor plan of Beijing courtyard house (Lo, 2010)

Similarly, the Vanke 5th Garden project (see Figure 43) located in Guangdong province Shenzhen city is also a pastiche. At the design stage, architects investigated the lifestyle of people in Southern China, reviewed the features of local culture,

considered local climate, borrowed the courtyard house style of Beijing, made surveys on the old-line towns around Yangtze River Delta, and researched the Hui style architecture in Anhui province. Eventually, they combine all these aspects together aiming to create a “complex mood of Chinese tradition (Zhu, 2006)”. Unfortunately, without a proper methodology, correct direction and reference, the result is the use of traditional characteristics as the decoration on the modern buildings rather than the representation of the essence. From Figure 44, the section of one example building does not reflect any traditional Chinese style. The shape of the roof is a right-angle triangle, which does not appear in any dynasty’s buildings or records. Also, the main structure relies on the structural wall that are commonly used in modern concrete buildings instead of the timber columns. Thus, the good purpose of Chinese mood becomes a mixture of everything but is not traditional. Another example is the Fashi District project in Fujian province Quanzhou city. Although the aim of this project is to renew the historic district, the result becomes a pseudo-traditional style, as shown in Figure 45. Therefore, from these examples, if the two major aspects of floor plan and section both do not contain traditional features, this representation of Chinese style could be said to be a failure



Figure 43. Vanke Fifth Garden project (Zhang & Tang, 2011)

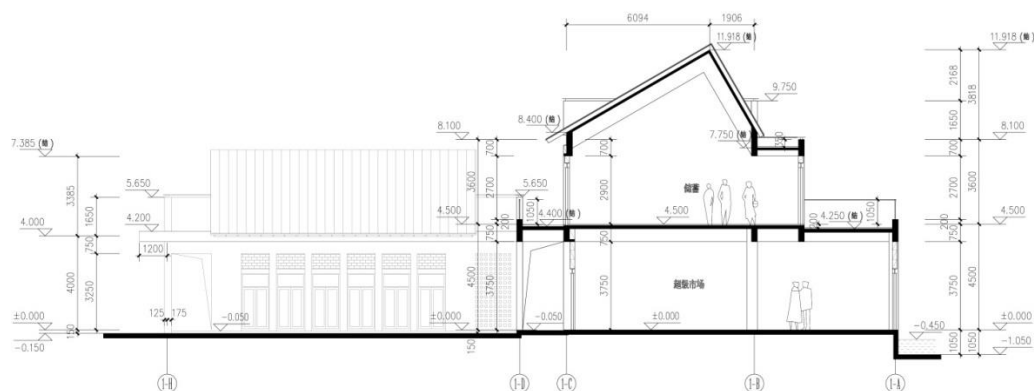


Figure 44. Section of one building in Vanke Fifth Garden (Zhang & Tang, 2011)



Figure 45. Fashi District project (International Stadtbau Atelier, n.d., p. 104)

On the other hand, the Pritzker Winner (2012) Shu Wang has some unique experiments on a revival of the Chinese style. Take the Tiles Hill project – New Reception Centre in Xiangshan Campus (shown in Figure 46 and Figure 47) opened in 2014 as an example. Wang is an expert in Chinese ink painting and his architectural design concepts are closely related to the philosophy that form the basis of Chinese ink paintings. As Wang says by himself, the Tiles Hill project is inspired by the appreciation of Chinese landscape ink paintings (Yang , 2014). As shown in Figure 47, there are three stages, depicted as a journey visiting the mountain. Before arrival, it is the outer view outside the mountain. On arrival, it is the inner view within the mountain. On departure, it is the metaphysical review of the mountain. During this movement, the feeling and understanding to the landscape becomes deeper and more impressive. This hidden philosophy of Chinese traditional ink painting is perfectly represented by Wang in his architecture, with the respect to the traditional arts. In addition, Wang also spares no effort to revive traditional constructional skills. As mentioned in the last section, rammed earth wall construction has a long tradition in Chinese architecture and Wang frequently uses this. In this project, he and his team build up a lab to test the rammed earth technology and eventually they made the strength of such wall four times that of reinforced concrete wall (see Figure 48) and this is the first time that rammed earth walls are used in modern Chinese buildings (Chen, 2014). Apart from these, the timber supporting structure of the roof and its proportion (see Figure 49) are directly inspired from traditional roof forms and the *dou gong*. This is a transformation from traditional architectural element to a modern design, which is a new approach to the

revival of Chinese style. As Wang points out, “we cannot go back to the tradition, but tradition can be revived” (Li, 2013). As the pace of modern civilization, people’s lifestyle has been changed, thus, the “form” of tradition may no longer exists or may not suit the modern habit. But the spirit of tradition cannot be discarded. Wang’s work is valuable because he tries to revive the tradition, including the arts, philosophy, skills and style, and meanwhile modernising the tradition to give it a new life. Only in the way of applying the tradition under modern condition can it be passed on generation by generation. And of course, the foundation of Wang’s design concept is from the traditional Chinese architecture, which is distinguished from the previous failure examples. Similar examples such as the China Pavilion of 2010 Shanghai Expo, called ‘Crown of Eastern’, are also inspired and rooted in the Chinese *dou gong* although it does not use *dou gong* directly. Overall, in these examples, the Chinese style does not reflected directly in showing traditional elements, but by applying invisible and complex Chinese impressions. This is an innovative approach of “Renaissance of traditional Chinese style”. But the essence and foundation must be the real Chinese style, which requires architects return to study and respect tradition in a serious manner.

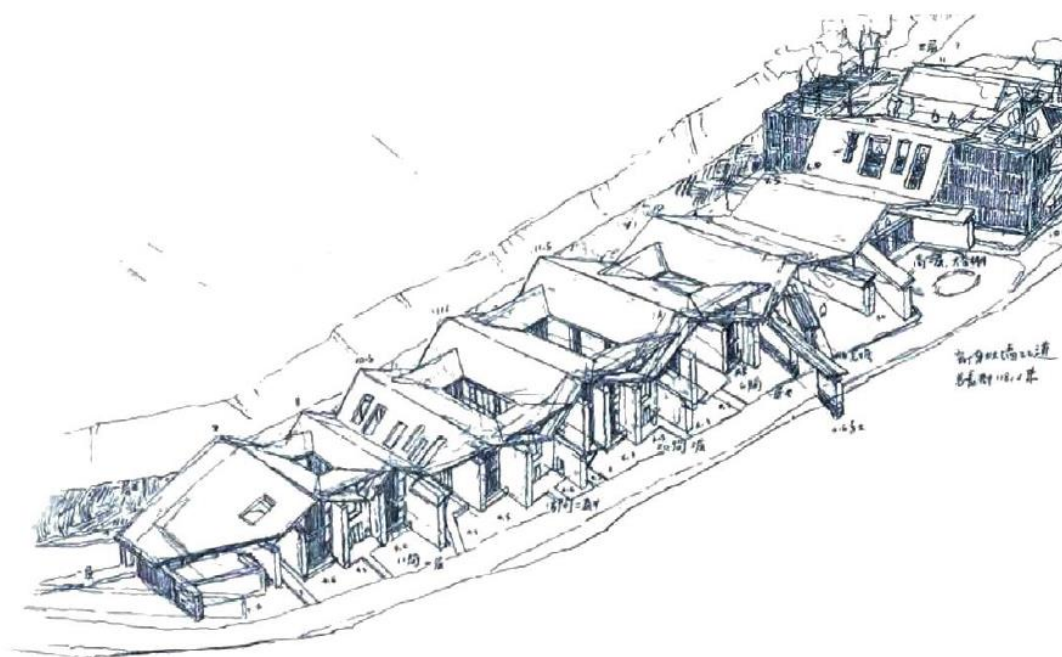


Figure 46. Sketch of Tiles Hill by Shu Wang (Wang, 2014)

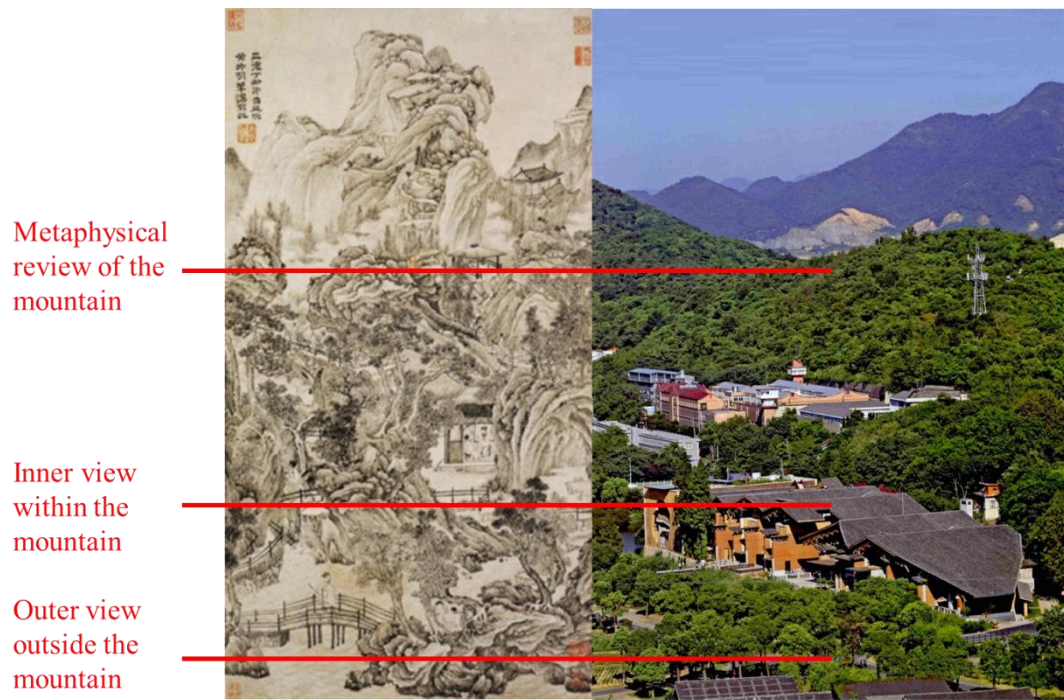


Figure 47. Comparison of Chinese ink painting with Tiles Hill project, edited and explained by the author, original figures (Yang , 2014)



Figure 48. Lab of rammed earth wall (Chen, 2014)

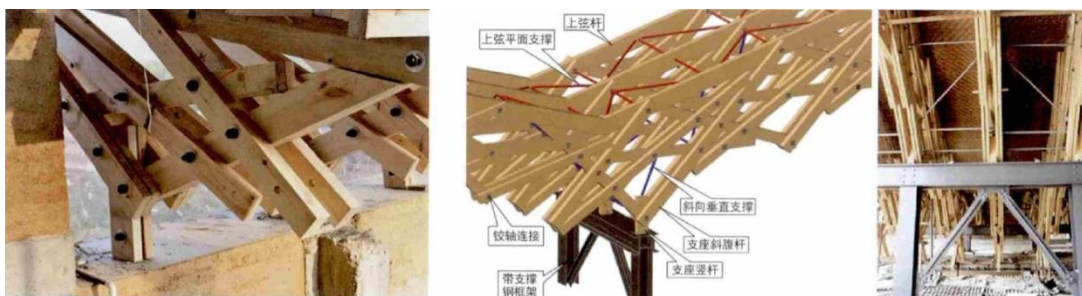


Figure 49. Timber supporting structure of the roof (Shentu, et al., 2014)



Figure 50. Crown of Eastern, Shanghai

1.1.2 Relevant methods and techniques in heritage studies

With the rapid development of digital techniques in architecture over the last 25 years, it is possible to re-discover the value of the lost or damaged architecture by transforming two dimensional physical information recorded in the historical literature into three dimensional digital representations (Webb & Brown, 2011). This plays a significant role in heritage studies. Using parametric (Li, et al., 2013) and shape grammar techniques (Li, 2001) (Wu, 2005) it has been shown possible to describe the relationships in a digital design environment that describe the traditional designs in an algorithmic way. Consequently, further analysis can be made together with a better level of understanding and interpretation. In turn, this can significantly aid understanding, in restoring and recreating examples of traditional Chinese architecture, or in designing contemporary examples that are based in and respect traditional geometries and values. Several examples are given to review the relevant methods and techniques in heritage studies.

Palladio's Villas are frequently used in this area. Sass has done a project of computational analysis of the villas by finding a method of reconstruction, using computational devices to build, represent and evaluate Palladio's un-built villas in three-dimensions (Sass, 2001). *The Four Books of Architecture*, which is a general

rulebook of the villas containing text and images explaining Palladio's design and construction systems was reviewed as a reconstruction reference. But in the rulebook, only one and two-dimensional data (Figure 51 shows Palladio's original 2D drawings) was offered. Most of the physical construction data needed to execute a full reconstruction of an un-built building was missing (Sass, 2001). The project presents a new method of reconstruction through the definition of construction rules, in addition to shape and proportional rules defined by previous scholars together with the utilisation of 3D printing (see Figure 52) and texture mapped renderings as tools (Sass, 2001). During this process, one and two-dimensional data is transformed into three dimensional representation. The rules and computational analysis process are the essence in the reconstruction, such that the manual of rules are used as the input and representation method as an output. After the development of such method and the testing on the selected case study, this analysis method could be used to recreate all 24 of the villas found in the *Four Books*. And in general, from this project, a broader use of this strategy and research methodology could be used as a reference in other similar research context for different types of architecture.

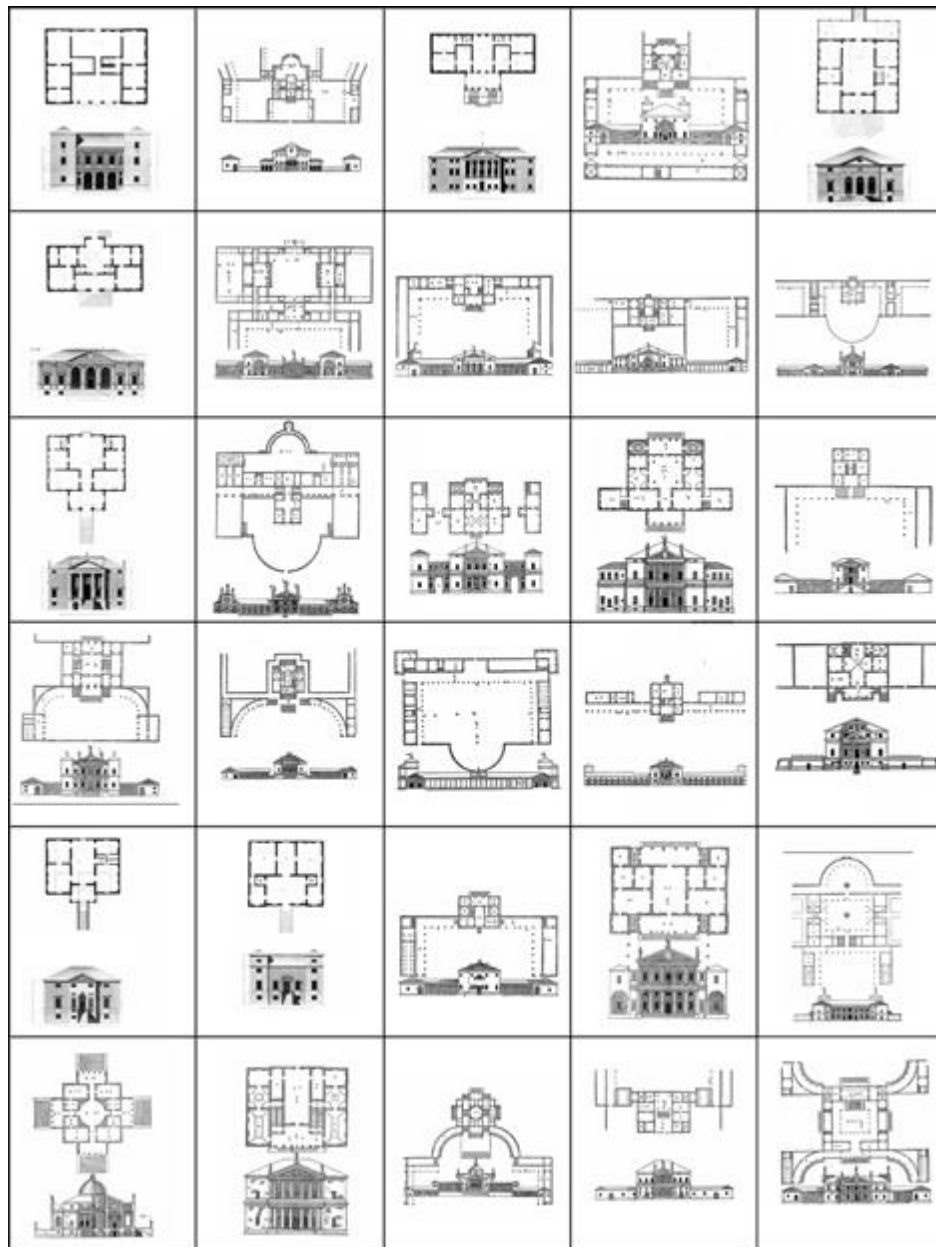


Figure 51. Palladio's original drawings (Sass, 2001)



Figure 52. 3D printing techniques used to view models in physical form (Sass, 2001)

A more recent project of the digital reconstruction on the alternative design of the Mackintosh' Scotland Street School in 2014 done by Di Mascio for the Hunterian Art Gallery is another good example (see Figure 53). The aim of this project is to visualize other design solutions that have never been built. To visualize the unbuilt design option of pale yellow Dullatur sandstone as the material rather than the red Locharbriggs sandstone ashlar used for the built building (see Figure 54), archive drawings (see Figure 55) together with text description and information (Anon., 2014) are used as the primary source to produce the digital model. There are mainly two challenges during the digital reconstruction process—one comes from the old drawings and the other comes from the material choice (Di Mascio, 2015). When transforming the archive drawings and text information into the three dimensional model, difficulties were found as there are imperfections in old drawings. For the same component or element, drawings of different views may present different size, shape or position. In other words, these imperfections could be put down to human error when these drawings were originally produced. To overcome the inconsistency of the drawings, tests and revisions are made repeatedly to find out the possible and reasonable solution in CAD. Eventually, the digital model has all the components consistent as a building. When applying the texture to the digital building, determining the colour and shape of the stones is another challenge. To simulate the texture as close to the designed one as possible, based on the investigation on the

same material used for other buildings in Glasgow at the same period, various combinations of the colour and shape texture were tested on the digital model to find out the best matched result. Therefore, the digital modelling is effective in testing and revising to solve the problem of imperfection in source, and powerful in visualizing the design concept to represent the unbuilt or lost architecture.



Figure 53. Perspective from S.E., rendering based on Mackintosh's earliest surviving drawings of January 1904 and showing his specification for pale yellow Dullatur sandstone (Di Mascio, 2014)



Figure 54. View from N.E. (McAteer, 2011)



Figure 55. North elevation, January 1904 (Office, 1904)

The church of Sagrada Familia church in Barcelona (see Figure 56) is a notable example of using computer aided techniques in its construction process. The starting

of the construction of the original gothic revival design by Villar began in 1882 but one year later Gaudi redesigned the church significantly with his renowned freeform facade. During 1911 when Gaudi became ill, he realised that in the event of his death it would be almost impossible for continuators to finish the church based on highly plastic architectural language; therefore he decided to form a more rational approach to the design, such as the use of hyperboloids or ruled surface geometry (Burry, 2005). In 1926, the primary information source was lost when Gaudi died in an accident. And even, the majority of his architectural drawings and models were destroyed during the Spanish Civil War of 1936—1939. From 1980 onwards, Burry joined the construction and research team with the introduction of Computer Aided Architectural Design, particularly, the writing of proprietary software, such as Autolisp scripts in AutoCAD, in order to interpret and enhance the understanding of the complex geometry. At the beginning, model makers painstakingly restored the fragmented pieces of the original models, which were then converted into digital representations. Later, these digital representations were translated into physical stone pieces by computer aided manufacturing techniques for the continuing construction. In this example, the construction time is much longer than the lifetime of the original architect, with the accidents of losing the vital information. The process of interpreting the freeform language into geometric shapes, as well as the support of CAAD in investigating the lost information, allowed the construction to continue after more than 120 years of the original design.



Figure 56. Sagrada Família Nativity façade

Since around 2000, parametric modelling started to be widely used in architecture (Woodbury, 2010). Since then a number of successful buildings designed using parametric techniques, such as the Swiss RE building, Leadenhall St, London (known popularly as the Gherkin). And the growth of the use of algorithmic design in architecture, and in particular parametric techniques, is obvious. Meanwhile, the growth in the interest and application of parametric techniques in the built environment is exemplified by the fact that the classical parametric design example—the Gherkin (at a scaled down proportion, see Figure 57), is a selected project for the 2015 Constructionarium, a UK national civil engineering student internship, held in Bircham Newton, in which the author participated. More details on this project can be found in 9.4 Appendix 1 of this thesis.



Figure 57. Gherkin (at a scaled down proportion) in the 2015 Constructionarium

Moreover technologies such as CAD, multimedia, virtual reality and internet, contribute significantly to the architectural heritage studies in recent years. These technologies are not limited by the research targets, and “can make to the presentation, understanding and preservation of the rich architectural heritage which exists in almost every cultural context” (Maver & Petric, 1999). In the research that Maver and Petric carried out, they defined virtual reality as: “an information technology which can provide a convincing, and enhanced, experience of environments which

- i) exist, but are too remote, costly or hazardous, to visit
- ii) don't yet exist but are planned, such as architectural designs or urban plans

iii) never will exist, other than in the imagination

iv) existed in the past and are now threatened or already lost” (Maver & Petric, 1999).

They provided a series of work concentrating on Virtual Heritage. Figure 58 shows an example of The Glasgow Directory On-Line which allows users to experience the virtual city as if they could experience the real one. And their research result showed that “the responses of both the general public and heritage specialists to the concept of Virtual Heritage has been overwhelmingly positive and we can anticipate rapid progress in the development of the technology and its effective uptake” (Maver & Petric, 1999). After fifteen years, their anticipation seems completely true, although at that time parametrics was not a key word in the whole concept. But with such a background, it is obvious that the traditional Chinese architecture lies within the four categories listed above, and with cultural significance. Together with the developing technologies, that are, the digital techniques proposed in this research, it is also anticipated that convincing and positive progress will be made throughout this research, and the outcomes will benefit both research and practice.



Figure 58. Frame from Glasgow Directory On-Line (Maver & Petric, 1999)

1.2 Aims and objectives

1.2.1 Research question and research value

The research question is:

To investigate to what extent and how to interpret and represent the traditional Chinese architecture using the research based on the rulebooks and various digital techniques.

The aim of the entire research is to better understand the design concept, structure and guiding principles behind Chinese traditional architecture and the applicability of parametrics to this style. This involves exploring algorithmic representations of the rules, and building digital models of the building elements, as well as investigating the relationships between the composing elements.

The longer term aim of this research is to develop a powerful digital tools to aid in restoring or recreating some damaged or destroyed examples of traditional architecture. With the guiding rules captured effectively, such an environment can also aid in providing new design concepts for contemporary buildings that properly respect traditional styles. The aim is to build these rules within a parametric design environment.

In recent years, as China develops rapidly, a growing interest in Chinese style or Chinese elements has become prevalent internationally in architecture, or even in a wider design context. This timing coincides with the profession, politician and general public moving away from a Modernist agenda looking more towards “what we formerly destroyed or ignored for what it can contribute to the future” (Sowa, 2005). On the other hand, running on the way of recreating Chinese style, inappropriate examples and pastiche appear frequently, leading to the misunderstanding and confusion that what is the real Chinese style and how to present it properly and effectively. This research aims to support in helping to support both issues.

The value of this research lies in its demonstration of applying digital techniques to uncover lost, unclear or fragment information of traditional Chinese architecture to enhance the understanding of such knowledge. Although there has already been a number of research projects on the topic of Chinese architectural history within the academic community, the focus of the research presented here differs in two ways. Firstly, this research augments the works of traditional approaches done by architectural historians, by solving the problems that historical materials cannot provide answers to. Thus, this is a complement to the interpretations to the ancient literature and archaeological sites. Secondly, the digital techniques used in this research are of an internationally standard and understandable, thus,

the presentation of traditional Chinese architecture using such techniques for a wider audience and architects will not be limited by the prerequisite of a profound background in Chinese architecture and Chinese culture. In other words, the difficulties coming from complex cultural aspects hidden in the Chinese architecture will be reduced to architects and researchers, whatever their architectural history knowledge level and cultural background, and in turn, reduce inappropriate designs in practice.

The value of this research also lies in the illustration of the digital techniques, especially parametrics applied to a novel target of traditional Chinese architecture, rather than the commonly used area of complicated shapes and curved surfaces of contemporary architecture. Although there have already been numbers of research projects on the topic of digital representation of various architectural styles, there are three distinguished contributions to this research. Firstly, the Chinese style (on a more general level, Eastern Asian style including those in Japan and Korea) is unique and different from any other styles in other countries in both design principle and construction. The possibility and limitation of digital techniques on such a target is awaiting deeper investigation. Currently this topic is not well researched, so this research will bridge the research gap between traditional Chinese architecture and digital techniques. Secondly, an emphasis is placed on the process of constructing digital representations and what can be learned from this in particular, how to deal with inconsistencies with incomplete information, as well as how to transform the rules created by ancient people into the rules used in the programming of machine language. Thirdly, when combining these two contributions, a primary design reference of applications is gradually accumulated, and this could be developed as a powerful database in digital tools in the future, such as the elements and options used in VisualARQ for Rhino (Asuni, 2015).

1.2.2 Research objectives

Objective 1: To rationally understand and analyse the current situation of Chinese architecture that relevant to this research, then propose a proper and effective research scope.

Rationale: As introduced in previous sections, since Chinese architecture has a very long history and distributes in a huge territory, there are a variety of types and forms according to period and location. On the other hand, Chinese architecture develops continuously and there is no exact boundary among the time or location. And if also considering the research materials left, it is important to figure out the scope of this research. In other words, the type and form of architecture need to be carefully

selected such that, they must be typical and symbolic, as well as there must be reasonable materials remaining to begin with.

Objective 2: To systematically review and document relevant historical literature, mainly the two rulebooks, and analyse these research materials.

Rationale: A better understanding of the selected styles and forms must be obtained based on both literature and extant building examples, in order to summarize the features of such styles and forms. Particular focus will be placed on the understanding and summary of the rules and regulations of the ancient design principle recorded in the rulebooks. This is the foundation for transforming the ancient rules into the algorithmic rules, and in turn, the basis of digital modelling.

Objective 3: To review relevant previous research that targets traditional Chinese architecture in CAD environment or could be useful to CAD representation, and that incorporates the use of digital techniques in heritage studies.

Rationale: In order to select and experiment the proper digital techniques, the previous research on the use of digital techniques as an analysis or presentation technique needs to be reviewed in relation to heritage studies. Selected examples will be given as references. Meanwhile, the previous studies on Chinese architecture in relation to a CAD environment or algorithmic representation are also essential in order to understand what has already been achieved in terms of research, what is missing and what could be expanded in this research. In particular, parallel research of the Shape Grammar approach to this topic will be given special attention.

Objective 4: To develop a consistent and systematic process based on the work in objective 1 to 3 in order to digitally represent three case studies of important elements in traditional Chinese architecture.

Rationale: The use of case studies to formulate a methodology enables the consistent technique of digital representation to be built up, developed, and tested. It is predicted that the selected three case studies will build up a framework on how to digitally present Chinese architecture including the overall proportion and detailed element, considering both cultural meaning and functional arrangement. Although the three case studies will not cover every aspect in Chinese architecture, they are the basic foundation and the essence for further studies on any other aspects. In addition, the three case studies have close inter-relationships with each other so if any one of them is missing, the frame is incomplete. It is also predicted that using the three different cases will have the result that possibility and limitation of digital techniques

on such target can be examined, difficulties during the process can be learnt and suggestions can be raised up.

Objective 5: To design contemporary examples that respect traditional values guided by the result of this research, and also spread the findings in education.

Rationale: To apply the findings in practice and education is an important way to prove and review the research. Through the way of suggesting architects, designers and students alternative options rather than conventional ways when designing traditional Chinese architecture, the implications and limitations of the research in traditional rules and digital techniques can be further understood. In addition, this is also a basis for the future to provide an option to restore and rescue damaged or disappeared traditional architecture.

Objective 6: To discuss and analyse the case studies and applications carried out and make key conclusions, as well as compare and summarize the key features of different approaches in order to conclude this research and suggest possibilities for improvements and future works

Rationale: Reviewing and reflecting the case studies and applications will lead the values and limitations of the whole research to be fully understood. From this, the methodology and process utilised in this research can be refined in order to further develop it as a system for future research in relation to Chinese architecture on different scope and in the area of digital heritage. In addition, to this process, the findings in this research can be evaluated in order to present it as a general guide or database for future design using the digital tools.

1.3 Methodology

As stated in the previous section, the Pritzker Winner (2012) Shu Wang's design concept is to revive a traditional Chinese style; to respect to the arts and philosophy and the utilisation and development of the traditional skills, the utilisation of modernization of the traditional elements and symbols. Although expressions vary, there is a dominant spirit, which all the manifestations root back from the real tradition. This is the way to avoid pastiche. Therefore, the study back towards the ancient rulebooks is necessary in order to understand the ancient rules and concepts, and in turn, to obtain the definition of real tradition. During this process, previous research on the rulebooks and traditional Chinese architecture are effective and complementary to overcome the difficulties in the original rulebooks.

Wang also spares no efforts to demonstrate that the revival of tradition must be based on a contemporary way to modernize it and give it a new life. If under a modern condition, tradition approaches can be applied in practice, it can be inherited by later generations. Therefore, to devise a proper way that suits modern design habit and trend is important. Based on the reviews in previous sections, digital techniques and in particular parametrics are reasonable assumptions as a starting point to play the role of contemporary method to revive the tradition. In this way, the Chinese tradition will not be a dead end in literature, but gradually become internationally accepted, understood and applicable to fit the new environment in the future.

Based on these two aspects of the research context, the research process needs to be outlined. According to the previous sections of digital techniques on heritage studies, the original sources normally include drawings, text information and extant examples. However, difficulties also come from these original sources, for example, the imperfections, inconsistencies and missing parts of the information. Digital techniques are efficient supports in solving such difficulties in different cases as shown in previous examples. And in turn, this is the advantage of digital techniques. In order to represent a certain style of lost or damaged buildings, an effective method is to select proper case studies with a clarification of the target boundaries and limitations.

As introduced in previous sections of Chinese architectural history, timber frame architecture is the most commonly used and highly developed type in most regions in all dynasties, and unique in the world. Thus, although other structures such as stone or brick architecture also existed in history, timber frame architecture is the most symbolic type to be used to represent a traditional Chinese style. Figure 59 shows the example of the China Pavilion in 2015 Milan World Expo. This building is inspired by the *Tai Liang Type* (see Figure 9) timber frame architecture with the character of Xie Shan Type roof style (see Figure 83, row three, the second building). Meanwhile, as this research relies on the ancient literature and extant examples, the focus will be placed on the official and public architecture, for example, palaces and temples, rather than civic houses, simply because more recorded materials and extant examples of such architecture could be found. But this does not limit the findings to be used only in official and public architecture because the rules are transferable. In addition, as the joint structure *dou gong* plays a significant role in Chinese architecture and unique in the world, it is also one of the symbols of a traditional Chinese style.



Figure 59. 2015 Milan World Expo China Pavilion

According to the current status in urban planning and architectural design, major failures could be summarized as the following aspects. Firstly, the floor plan and section do not represent a traditional Chinese style. Thus, the overall proportion is incorrect. Secondly, the traditional constructional features are omitted, for example, the use of columns as major load bearing structure are replaced by concrete walls. This is also reflected on the floor plan and section. Thirdly, the joint structure *dou gong* either disappeared or is presented in a very abstract way, which does not well deliver its functions and values in history. Consequently, three case studies will be discussed : floor plan, section and *dou gong* of the timber frame architecture. And in these selections, the roof, which is also one of the symbols of traditional Chinese style, will be partially covered by the work of section and *dou gong*. When these three aspects are well studied, further studies such as elevation, patterns of door and window, decorations could be carried out in the future with the same methodology.

After the selection of the case studies, the algorithmic representation and experiments of the digital modelling will be carried out on the three case studies and comprehension will be improved by solving the difficulties in the modelling process. Then investigate the potential applications based on the above research in generating new designs. This could be a foundation for the further development of a database in digital tools. Consequently, the methodology proposed here will benefit both parametric research on traditional Chinese architecture and the possibility of application in design practice.

1.4 Potential outcomes

Outcome 1: An innovative methodology to study traditional Chinese architecture using digital techniques, particularly parametrics, based on three case studies.

Outcome 2: An interpretation and documentation of the two historical rulebooks (the parts related to the three case studies) and relevant research materials.

Outcome 3: An understanding of the process that transform the ancient rules to the algorithmic representation.

Outcome 4: Digital representations of the selected three case studies, and the evaluation of the process in terms of the difficulties and solutions.

Outcome 5: A further proof that the traditional Chinese architecture recorded in the ancient rulebooks is rule-based and could be parametrically presented.

Outcome 6: A demonstration of applications based on this research producing new designs with the respect to the traditions.

Outcome 7: A rediscovery and appreciation of the traditional values based on this research.

Outcome 8: A comparison between different approaches towards the research on traditional Chinese architecture.

Outcome 9: A reflection and conclusion of the research process to produce refined and robust methodology for future research, and to produce design suggestions in education and a practical project as a basis for the database of the digital tools.

Outcome 10: A suggestion on the possible future research directions.

1.5 Limitations

The nature of the case studies means that only selected elements of architecture with typical reasons (as stated in previous sections) will be explored. With such selection, the approach of digital representation of Chinese architecture with these three case studies has its natural advantage and disadvantage compared to other approaches. The advantage is stated briefly when given the reasons of the selection and will be further demonstrated in the following chapters. The natural limitations will be described here in order to make a clear scope of this research and explain why with such limitations the methodology is still proposed in this way.

Firstly, in *Ying Zao Fa Shi*, “the rule of material” such that setting “the rule of eight grades of standard timber material (called *Cai*)” as a standard to distinguish building

levels is the spirit of the rulebook. But in this research, this rule is not an individual focus presented in a single chapter, neither as a starting point for the entire research as it was put at the very beginning in the carpentry volume of the rulebook. Instead, this rule is involved in all the three case studies as one of the algorithmic rules in modelling. This does not follow the “basic concept” (Feng, et al., 2014, p. 414) of the rulebook. However, *Cai* is a practical principle that when explaining together with a concrete element (such as floor plan, section or *dou gong*), its meaning is clearer. Also, considering this research is not purely on the history area, to transform this practical rule into the algorithmic rule by integrating it directly into the modelling process will result in better investigation on the relationship between Chinese style and digital techniques.

Secondly, the rulebook considered both design and construction process at the same time in ancient period (Pan, 2009, p. 260). But as this research does not focus on the construction area, the material consumption and structural analysis are not an interest. Thus, the absolute values of dimensions will not be calculated unless in the purpose of checking data with extant buildings. Instead, the modular units will be used to explore the proportions. This also reflects one of the features in parametrics that relationship is a key in modelling.

Thirdly, in *Gongcheng Zuofa Zeli*, “the rule of material” defined in *Ying Zao Fa Shi* has been changed to “set the length of *dou kou* (definition see Chapter 5) as a standard length to determine all the other components of timber structure”. Therefore, naturally, the length of *dou kou* should be used as a basic parameter in modelling. And indeed, in Qing Dynasty, the design concept followed the process of determination of the length of *dou kou*, then the dimension of *dou gong*, determines the scale of the whole building. Nevertheless, to follow this process, the difficulty lies in the complexity of *dou gong*. This joint component has an extremely complicated structure, and meanwhile, to transform its structure into an algorithmic presentation and develop a system parametrically represent it, the difficulties are not negligible. Ancient builders followed such rule mainly because of their long term practical experience but they rarely understood the principles (Pan, 2009, p. 260). In this research, making a model that looks similar as the ancient ones is not the purpose. To build up logic for parametric modelling, from easy to difficult is a reasonable process. Consequently, to begin with the floor plan and section in order to have a primary understanding to the rules and an overall idea to the general proportion, then move forward to the complicated detailed element is proposed in the methodology. In addition, in this way, if the complicated element fails in this test, large scale research ignored. More details will be discussed in Chapter 5.

Fourthly, the sequence of investigation into the rules for each case study may vary from conventional research. Different attempts will also be made to compare and optimize the modelling process. For example, in section case study, the primary consideration is placed on the position and height of the columns, rather than the roof curvature. This is because from the perspective of a parametric approach, the

position and height of the columns determines the roof shape in the initial test. And after the overall frame of the section is built up, variations could be made based on it. If the process is made in the opposite sequence, the roof curvature cannot determine the rest parts of the section. Therefore, the decision tries to balance both ancient rules and traditions, as well as the algorithmic rules in parametrics. A similar concept could also be found in Andrew Li's research of shape grammar approach to Chinese architecture (Li, 2003). On the other hand, when trying to combine the section together with the floor plan to form a complete frame, the sequence of representing the section will be slightly changed in order to be consistent with the algorithmic expression of the floor plan, and optimize the whole algorithm. Therefore, the sequence of the rules will follow the algorithmic requirement, rather than being kept exactly the same as in the rulebooks. This should not affect the outcome at all as long as rules are fully considered and covered in modelling process.

Apart from these, the research presented here relies on the architectural historians' work and their interpretation to ancient architecture, as well as the author's interpretation to their work and the rulebooks. Errors and inaccuracies may exist in the information collected for the modelling process. However, this does not affect the value of this research since the parameters and algorithmic logic in parametrics are fully adjustable, which is one of the significance of this technique. Additionally, each digitally presented model is either a conceptual model based on the rules recorded in the rulebooks, or presents a range of examples that are consistent with extant buildings. Exceptions may exist if new information is provided by historians or new heritage sites would be found in the future. But again, the parametric tool is very powerful that can be modified to cover the new data range, and the applications derived from such models could be broader than the models themselves also due to the adjustable parameters.

The methodological approach also limits the research in terms of investigating both areas of computer aided architectural design and history of architecture. Due to this breadth, various digital techniques and traditional Chinese architecture are both focused on, meaning that depth is limited in both areas compared to those primarily concentrate on only one area. However, as stated before, to bridge the gap between the two areas is one of the goals, to make a contribution to both areas. Indeed, sufficient studies on Chinese architecture are made and relevant and proper techniques are selected in this research.

Chapter 2 Research context

2.1 Historical references

It has been said that to study the history of Chinese architecture without knowledge of its constructive rules is like studying the history of English literature before learning English grammar (Liang, 1985). To interpret and represent traditional building styles, it is necessary to understand their design concept and structure. Therefore, a brief review of the rulebooks and relevant historical references is necessary. As mentioned in Chapter 1, it is fortunate that two important rulebooks survived: *Ying Zao Fa Shi* (Building Standards) from the Song Dynasty and *Gongcheng Zuofa Zeli* (Structural Regulations) from the Qing Dynasty, which are called “two text books of Chinese ancient architecture” by Liang (Liang, 1985). These two “text books” summarized previous builders’ design concept and constructive skills in the form of experiences, which established the official standards and instructions during those two dynasties respectively. As a starting point, the review and analysis on the two rulebooks are key factors in understanding architecture of those two dynasties, and in general, all the ancient architecture. From these two books, key characteristics of Chinese ancient architecture can be identified.

2.1.1 *Ying Zao Fa Shi*

Ying Zao Fa Shi was compiled by Jie Li, the court architect of the *Hui Zong* emperor of the Song Dynasty. The first edition was not accepted by the emperor, while the second edition was published in 1103, mainly introducing regulations and standards in architectural design and construction. The book covers a very wide range of contents, which key contents include a basic civic plan regulation, masonry structure and carving, wood frame and structural carpentry such as column, beam, rafter, *fang* (small beam or lintel) and *dou gong* (joint, also known as bracket set), shape and style of door and window, tile and tile decoration, as well as coloured painting. Additionally, it also introduces the method of calculating material consumption and estimating the workload.

In history, all copies of the original print from 1103 and the copies of the reprint from 1145 were lost. Until 1919, a Chinese scholar Qiqian Zhu found a manuscript copy of this book in a provincial library in Nanjing. Zhu was so enthusiastic about this rare and important manuscript that he had it printed by a photo-lithographer in the same year and the publication aroused such great interest that a photo-lithographic facsimile of the same manuscript was published one year later in 1920 (Fu, et al., 1984). This lost and reappearance process causes problems in

understanding this book as well as delight. The way in which scholars solve these problems will be discussed later. Their solution is also a reference and inspiration for the method how to interpret and approach this rulebook using in this research.

The current copy used in academia is a reprint version in 2006 (Li, 2006), which has exactly the same form as the 1103 version that keeps all the contents and language as the original, as shown in Figure 60. *Ying Zao Fa Shi* is written in ancient Chinese grammar which has no punctuation, with Chinese Traditional Characters and vertical scripts in columns going from top to bottom and ordered from right to left, which is totally different from the current standard of modern grammar, Chinese Simplified Characters and horizontal scripts in lines. Therefore, the analysis of this book should start with understanding its contents and descriptions as accurately as possible, which is the primary challenging to overcome. Additionally, the measurement units in the Song Dynasty, such as Chinese *fen* and Chinese *cun*, are different from current international standards. Considering the purposes of this research that to interpret the rules parametrically, and the spirit of this book that is “the rule of material”, exact dimensional units (absolute values) will not be used, concentrating on the proportion and relationships of each factor by using modular units. The explanation of the measurement units and how to calculate the absolute values based on modular units will be discussed in Chapter 3. The original purpose of this book, content of each volume and appreciation to it are summarized as follows.

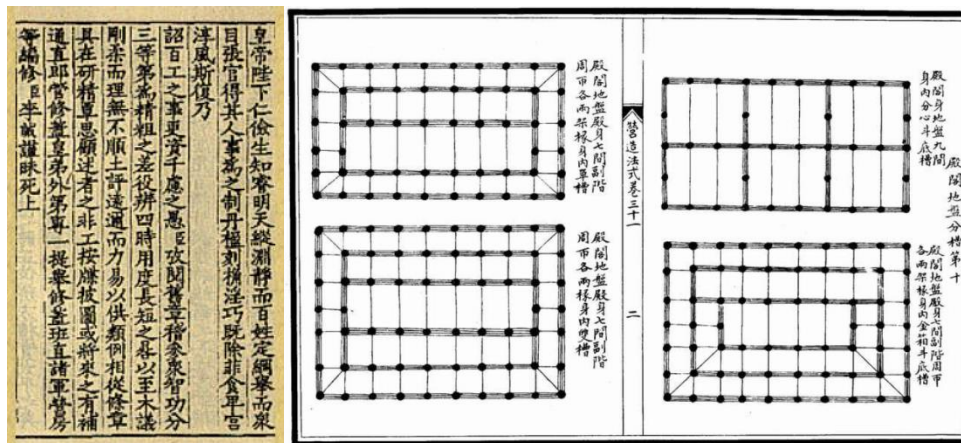


Figure 60. Sample pages of *Ying Zao Fa Shi* (left: text description (Anon., 1997); right: floor plan diagram (Li, 2006))

Ying Zao Fa Shi was the official building standard as a guidance of design and construction in the Song Dynasty. During the period of the Song Dynasty, with the rapid development of the society and economy, an increasing number of different levels and types of buildings were constructed which led to an urgent requirement of an official instruction. At that time, project leaders usually misstated the material

consumption before the project, and jerrybuilt in construction. This led the quality of buildings to be poor and brought danger to users. Apart from this, the design concept, architectural form and style varied by projects without consistent guidance. This led the architecture lost the unified style and could not reflect the owners' social class. In 1023, the imperial court proposed the regulation that project leaders, architects and builders must manage the project properly (Wang, 2013). But this did not work well as this regulation was based on individuals' management and decision, which was not reliable. In 1054, the imperial court issued an edict that if the building would collapse within seven years, the project leaders, architects and builders would be sentenced to felony (Wang, 2013). Again, this did not work effectively as there was no specific standard for relevant people to follow and for court leaders to inspect. Thus, the outcomes strongly relied on people's experience, and there was no prevention system to avoid problems.

To solve the problems thoroughly, there were three original purposes of *Ying Zao Fa Shi*. First, set the design guidelines to articulate the social status of feudalism reflecting by architecture. Second, establish a unified architectural form and style to guarantee a consistent level of detail and artistic effects. Third, define the material consumption and quantities as well as the workload to avoid corruption and embezzlement. The first edition was completed in 1091, called *Yuan You Fa Shi*. But this book had many drawbacks, conflicting with the practical work. The second edition was then compiled by Jie Li in 1103. Before he started this book, Li had directed more than ten large scale projects of palaces and temples in the capital city, gaining him rich experience in practice. During compiling, he referred to previous literature and old regulations, combining with builders' experience and ideas. Upon finish, the book included 3555 rules, in which 3272 were from practical experience and proved to be feasible for hundreds of years (Wang, 2013). Li discussed each rule with experienced builders, confirming it from scattered experiences to clearly-defined and rigorous rules.

This book consists of thirty-four volumes. Volumes one and two are the overall introduction to different types and components of the architecture. Volume three is about the foundations, masonry structures and carving of handrails. Volumes four and five introduce the structural carpentry system. Volumes six to eleven introduce the finished carpentry. Volume twelve includes three timber precast methods and bamboo weave method. Volume thirteen explains tile and cement processing. Volume fourteen focuses on the composition and colour matching of decorative painting. Volume fifteen describes the precast of bricks and ceramic materials. Volume sixteen to twenty-five presents the calculation of the workload required in the previous volumes. Volume twenty-six to twenty-eight outlines the material consumption of the components mentioned above. Volume twenty-nine to thirty-four are the selected diagrams.

The significance of *Ying Zao Fa Shi* is not "simply for its existing" (Li, 2001). The book is, in general, well organised, logical, systematic and rigorous which is quite

rare in ancient literature. Although some aspects such as the floor plan are relatively lacking in systematic description based on contemporary views, the whole book provides readers with a “rule-based and parametric” system (Li, 2001) for the ancient style buildings by giving general rules and ratios. Liang (Liang, 1983) even points out that the *Hui Zong* Emperor was a naive politician, but was an excellent artist. Meanwhile Jie Li was also good at drawing, calligraphy and music. Considering the rich contents and wide range knowledge included in the book, some descriptive rules occasionally omitted by Li is acceptable, and this may also be due to the loss in history. This book builds up the system of Chinese architectural style and records the design and construction process for the first time. Research on this book in recent years has always been a fundamental work for architectural historians, mainly based on conventional methods and views. To explore the parametric characteristics hidden in this book and in traditional Chinese architecture, digital techniques are utilized as a new attempt to approach this book.

2.1.2 *Gongcheng Zuofa Zeli*

Gongcheng Zuofa Zeli (also spelt as Kung-ch’eng tso-fa tse-le in the past) was compiled by the Ministry of Public Works of the Qing Dynasty in 1734 during the *Yong Zheng* Emperor as the official standard of building regulation (Anon., 1734) at that time. The book consists of seventy-four volumes. The first twenty-seven volumes introduce twenty-seven different types of buildings such as halls, city gates, residences and pavilions, and their structures, with actual measurement size and dimensions given as examples, making it useful for reconstruction of exactly the same buildings of the period. Volume twenty-eight to volume forty introduce the structure of *dou gong*, its size, shape and installation method. Volume forty-one to volume fifty introduce the method of producing door and window, stone structure, tile and soil work. All the above contents are guidance for design and construction. The last twenty-four volumes prescribe the choice and calculating of material, as well as labor.

In relative terms, *Gongcheng Zuofa Zeli* is linguistically more acceptable for current researchers since it was compiled in 1734, more than six hundred years closer to us. This is one of the most important functions in solving the difficulties when interpret the lost *Ying Zao Fa Shi*, and this will be discussed in details later. Meanwhile, more extant buildings from Qing Dynasty can be studied as practical evidence in support of this book.

Compared with *Ying Zao Fa Shi*, this book provides accurate size and dimensions for all the 27 types of buildings, which is a salutary record and making it useful for reconstruction. Conversely, this is also a shortcoming. *Ying Zao Fa Shi* introduces principles and general rules and ratios at the beginning then gives examples, which is

a highly summarized systematic guideline. Although it does not give the actual size of each component, it provides description of proportions. So the information is transferable and could be used for different scale buildings. In other words, this reflects rule-based and parametric features. But *Gongcheng Zuofa Zeli* introduces each type individually without an overall principle and there is no technical terms explained. For the aspect of the diagrams it contains, there are only twenty-seven cross sections of the twenty-seven types of buildings, but without many important details such as the shape of *dou gong*, decorative paintings or colours, which is also considered as a disadvantage since these details reflect the characteristics of the architecture in a certain period. Even, there is a lack of drawings illustrated the rest texts in the following volumes. In general, the editorial board “seems to have failed to grasp the essence of the standardization system and to have been out of direct contact with the artisans” (Fu, et al., 1984). Fortunately, there are still many surviving example buildings from Qing Dynasty, especially seminal pieces such as the Forbidden City and the Prince Gong’s Palace. These can be used for studies to overcome the drawbacks.

Research on this book was started by Sicheng Liang since 1930 together with scholars in Society for Research in Chinese Architecture. Based on his understanding and interpretation to the texts, he drew standardized diagrams by engineering cartography manually and he described his own method as “stupid effort made by a stupid person” (Liang, 2006). Considering his great contribution to the research of this book, it is not stupid although might be slow and inefficient. Unfortunately, many of his research work has been lost due to the Second World War and he has not completed the research on this book until he passed away. In order to improve Liang’s slow and inefficient conventional method to interpret this book and reflect the architectural style it recorded, digital techniques, especially parametric method is utilized aiming to reinterpret and summarize the rules intelligently.

2.1.3 Other relevant historical references

Apart from the two rulebooks, other sources are available as non-official references written by folk experts or experienced builders. For example, a book called *Ying Zao Fa Yuan* (Building Methods) introduces the structures of the riverside house type in Southern China, especially in Suzhou, Wuxi and adjacent cities. This book is written in 1935 by Chengzu Yao based on his heirloom material and diagrams and later revised by Zhigang Zhang (Tian, 2009). Similar as *Ying Zao Fa Shi*, this book also includes chapters on structural carpentry system, timber frame knowledge, *dou gong*, *ting tang*, *dian tang*, masonry, decoration and construction methods. It is based on private resources and experience, so considered as a folk publication rather than an official standard. But it is a repository of significant knowledge of traditional building styles. According to the content, it is a systematic and logic introduction to

the southeast China buildings, which refers to the merit of *Ying Zao Fa Shi*. In addition, this book introduces the construction and composition of Chinese gardens, which did not appear in the two official rulebooks but widely appeared in China, especially in Southern China. On the other hand, some different names are used in this book when describing same terms compared with the two rulebooks, which is normal as time passes by. But given that the two rulebooks already have two sets of names used in the two dynasties respectively, in order not to be confused, the names used in this book will not be followed in this research. Additionally, some of the descriptions in this book are different from the two rulebooks. In such cases, they are not considered as standard rules. In order to investigate the “rule-based and parametric” system, this book is treated as a support in understanding the two rulebooks, rather than a parallel reference. This is different from the previous research done by Tian (Tian, 2009), but aims to concentrate on the official and standard rules.

Qing Shi Ying Zao Ze Li (Qing Style Building Regulation) is written by Sicheng Liang in 1934 (Liang, 2006). It records Liang’s research work on official architecture in Qing Dynasty including their names, proportions, functions and design and construction methods with diagrams of plans, sections, elevations and other details. As mentioned before, Liang has done research on *Gongcheng Zuofa Zeli* with annotation and diagrams. This book could be considered as an extension of the interpretation to *Gongcheng Zuofa Zeli* which also relies on the investigation to extant buildings from Qing Dynasty. In addition, this book also contains information about the “secret” handbooks of craftsmen. Liang documents such information and summarizes it as regulations. In 1945, Liang reflected his own work in this book and pointed out that “in the past ten years it is found that there are many mistakes in this book and hopefully they can be revised in future republication” (Liang, 2006). Unfortunately, nobody has revised those mistakes after Liang passed away and this book has been republished in 2006 as its original version. Even though, this book is still an important complement in understanding *Gongcheng Zuofa Zeli* and architecture in Qing Dynasty, and in turn is a powerful reference to interpret *Ying Zao Fa Shi*. As one of the references for this research, the mistakes in this book could be ignored as evidence on historical architecture will be continuously found and understanding will be updated all the time. But Liang’s interpretation to the ancient rules is a useful basis to develop the ancient rules into algorithmic representation in this research.

Apart from these, the Lei family’s work and their records “the Portfolio of The Leis” make distinguished contribution in understanding traditional style architecture as introduced in Chapter 1. The maintenance and refurbishment work of the Forbidden City was significant in Qing Dynasty and many technologies and concepts used at that time cannot be exceeded or reproduced even until now. The Yuanming Palace was renowned throughout the world for its fabled charms and perfect splendour, extolled as the “Garden of Gardens” and the “Versailles of the East” during its

heyday. It was an imperial summer resort for the royal family. The Summer Palace literally meant "the Garden of Nurtured Harmony". It was mainly dominated by Longevity Hill and the Kunming Lake, and covered an expanse of 2.9 square kilometres, three quarters of which is water. In 1998, UNESCO included the Summer Palace on its World Heritage List. The Eastern Royal Tombs of the Qing Dynasty was the biggest cemetery palace, in which there lay five emperors and fourteen empresses. It was also included on the World Heritage List in the year of 2000. "The Portfolio of The Leis", as a completed textbook and precise guide of Chinese ancient architecture, was a precious heritage for the posterity to understand, study and repair the ancient architecture. In general, there were three main aspects of the design concept and characteristics of the Lei family. Firstly, an appropriate location was the basis of success. Secondly, the "symmetric rectangular" style was a dominant representation of imperial power. Thirdly, to immerse the architecture into the surrounding natural environment was the earliest idea of sustainability in the world. Up to now, there are more than 30 world famous architectural sites in China included on the World Heritage List, one fifth of which were designed by the Lei family, not to mention that their design concept also had impact on the traditional Japanese architecture.

Other references such as *Luo Yang Ming Yuan Ji* (Famous gardens in Luoyang City) and *Wu Xing Yuan Lin Ji* (Gardens in Wu Xing City) are also important resources (Peng, 2011) in introducing unique Chinese gardens and landscape. Also, as mentioned in Chapter 1, the book *Yuan Ye* (Craft of Gardens) is currently famous internationally and has been translated into English and French (Hardie, 1988) (Chiu, 1997). These historical references are considered as complements of the two rulebooks in the investigation of traditional Chinese architecture and interpretation of the rules.

2.2 Liang's research on the two rulebooks

"Not until the twentieth century did the Chinese undertake the study of their own architectural history, and in this the pioneer was Liang Ssu-ch'eng (spelt as Liang Sicheng today). By inheritance and training Liang was superbly fitted to the role fate assigned him—leader of the first generation of Chinese architectural historians." (Fairbank, 1985)

Liang devotes his entire life into the research on Chinese architecture, and produces two important annotation analysis on the two rulebooks: "*Ying Zao Fa Shi Zhu Shi* (The annotated *Ying Zao Fa Shi*)" and "*Analysis on Gongcheng Zuofa Zeli*". He provides deep interpretation to the rulebooks and summarizes his key findings in another important introductory book "A pictorial history of Chinese architecture: a study of the development of its structural system and the evolution of its types". To

unfold his main contribution, a summary based on Liang's research is given as a key understanding to the rulebooks.

There are five major concepts in *Ying Zao Fa Shi* (Liang, 1985):

First, modules used in *Ying Zao Fa Shi* are *Cai* (spells as ts'ai in the past) and *Qi* (spells as ch'i in the past). As mentioned before, the spirit of this book is "the rule of material" such that setting "the rule of eight grades of standard timber material (called *Cai*)" as a standard to distinguish building levels. Specifically, the term *Cai* has a twofold meaning. It is a standard-sized timber used for *gong*, or the "arm" of the *dou gong*; and all timbers of the same depth and width. There are eight grades of such timber, which are determined by the type and official rank of the building. Also, *Cai* is a module for measurement. The depth of each *Cai* is divided into fifteen equal length, and the width of the *Cai* is divided into 10 equal length, each length is called *fen*. Every measurement in the building, for example, the height and breadth of the building, the dimensions of every member in the structure, the rise and curve of the roofline, is measured in terms of *fen* of the grade of *Cai* used. When two *Cai* are used one above another, a block of six *fen* in height, called *Qi* is customary to cushion them by filling the gap. One set of measuring consisted by one *Cai* and one *Qi* in depth is called a "Zu Cai", or full material. Figure 61 shows this modular system. The measurements and proportions of a building in Song Dynasty are always expressed in these two modules. The use of modules of *Cai* and *Qi* is a basis and an essence to derive the algorithmic presentation and in turn, a significant part in parametric modelling.

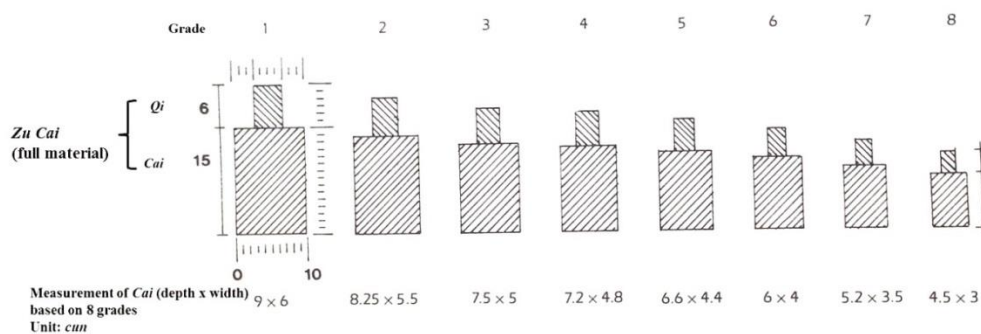


Figure 61. *Cai* and *Qi* in Song Dynasty

Second, *dou gong* (also translated as joint or bracket sets) is a unique and sophisticated Chinese element. "The function of the set is to transfer the load from the horizontal member above to the vertical member below" (Liang, 1985). More details of *dou gong* will be discussed in Chapter 5. Since this typical element is very important and symbolic, although it is complicated that this element itself could form

an individual research topic, it is included as one case study in this research in order to investigate the possibility to present it parametrically, and in turn to find out whether the traditional Chinese architecture is “rule-based and parametric”. Although in this research, the database including the features of all types of *dou gong* cannot be fully built up (and so far such database does not exist in the true sense), the possibility will be explored and the feasible methodology will be pointed out.

Third, the size and shape of a beam varies according to its function and position. The shape could be either straight or slightly arched. The circumference of a beam may vary according to its length, but as “the rule of material” defines, the cross section always retains, as a norm, a ratio of 15:10, or 3:2, between its depth and width using the module of *Cai*.

Fourth, “the rules governing the length and the diameter of a column are rather loose” (Liang, 1985), with the diameter varies from one *Cai* plus one *Qi* to three *Cai*. Considering the relatively loose definitions, when representing columns in the floor plan case study, they are illustrated as proper size circles; while in section case study, they are abstractly simplified as lines with certain length or cylindrical pipes. These simplifications do not affect the research of the ratios, proportions and relationships between different parts of the main structure, and meanwhile clarify the major parameters and rules to a maximum level. The shapes, variations and other details of the columns are out of the scope of this research so will not be discussed.

Fifth, the roof is another unique and symbolic Chinese element. *Ying Zao Fa Shi* provides rigorous definitions in designing the profile of the roof plane. Details will be discussed in 4.3 of section case study.

These are the major essences included in the structural carpentry volume in *Ying Zao Fa Shi* and will be covered in the three case studies. Other contents such as decorations, detailed parts of finished carpentry, colouring and construction methods are out of the scope of this research and will not be discussed.

Similarly, there are five key aspects in *Gongcheng Zuofa Zeli*:

First, the depth of *Cai* is reduced in Qing Dynasty rules. As introduced above, in Song Dynasty rules, the depth of the *Cai* is fifteen *fen* and the depth of *Qi* is six *fen*, resulting a total *Zu Cai* (full material) of twenty-one *fen* in depth. But modular system of *Cai* and *Qi* is changed in Qing Dynasty such that “set the length of *dou kou* (as shown in Figure 62) as a standard length to determine all the other components of timber structure”. *dou kou*, or mortise of the *dou*, for receiving the *gong*, is defined as the Qing module. It equals to the width of the *gong*, thus, it equals to the width of the *Cai* (ten *fen*) in terms of Song construction. The dimensions and proportions of all the parts of a *dou gong* are now expressed in multiples or fractions of the *dou kou*. The gap between the upper and lower *gong* (cushion block, *Qi* in Song style) is the retained six *fen*, or 0.6 *dou kou*. The depth of the *gong* (depth of *Cai*) is reduced from fifteen to fourteen *fen*, or 1.4 *dou kou*. Therefore, the *Zu Cai* then becomes only

twenty *fen* in total, or two *dou kou* in depth. Once the standard length of *dou kou* is confirmed, the dimensions of the building and timber materials are then determined. The use of modular system of *dou kou* is also an important foundation in deriving the algorithmic presentation and parametric modelling. In addition, since the rules in Qing Dynasty have certain relationships with the rules in Song Dynasty (a comparison is shown in Figure 63), this relationship is also a significant consideration in the algorithm and modelling, such that, the two systems can be considered at the same time and combined as one. And whenever required, they can be distinguished later.

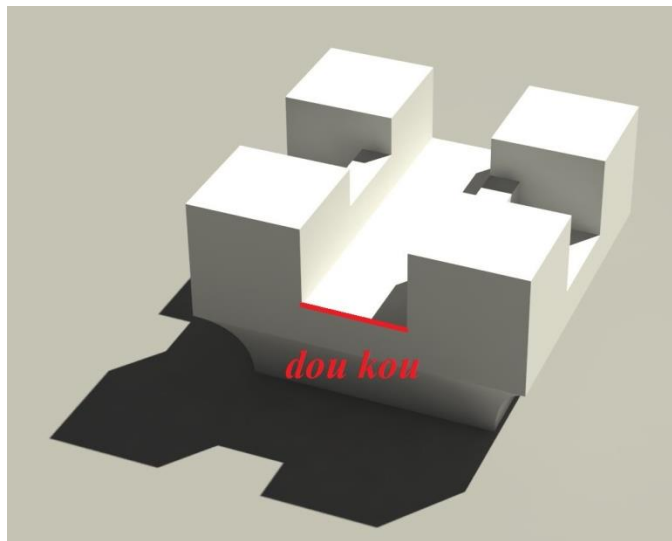


Figure 62. Definition of *dou kou*

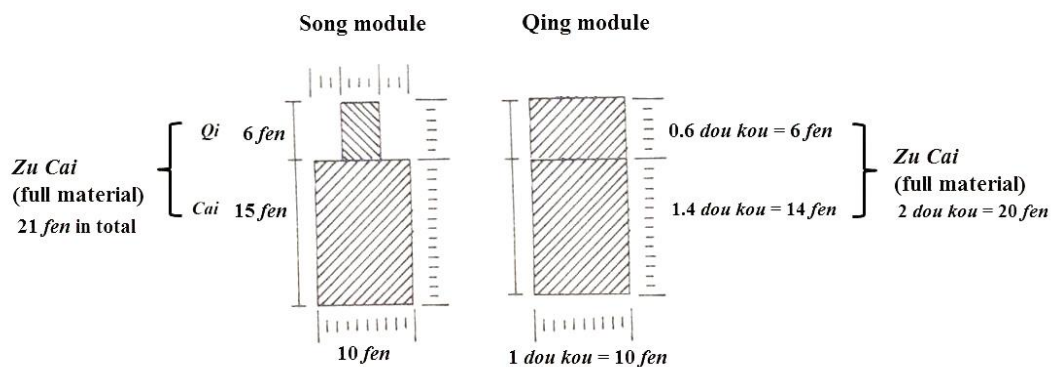


Figure 63. A comparison between Song module and Qing module

Second, *dou gong* is changed in terms of aspect and function. In Song Dynasty, *dou gong* has the *lu dou* (major bottom block) supporting several tiers of *gong* (arms) with open or plaster-filled gaps between. These tiers are cushioned by other small *dou* (small blocks). But until Qing Dynasty, these several tiers of *gong* are laid one directly on top of another with each tier having a two *dou kou* depth. Thus, the gaps allowing space for small *dou*, or *Qi*, are eliminated. This modification affects the general aspect of the *dou gong* as shown in Figure 64. Regarding the function, until Qing Dynasty, the structural function of *dou gong* is reduced and it becomes a more decorative element. On the other hand, apart from this aesthetic function, the number of *dou gong* determines the length and width of a building. “As the number of intermediate sets (of *dou gong*) is increased, the distance between them is strictly specified as eleven *dou kou* center to center” (Liang, 1985). Consequently the distances between columns, and in turn, the length and width of a building must be multiples of eleven *dou kou*. From these modifications, certain relationships of the rules between the two rulebooks can also be found. Therefore, in this research, when build up the algorithm, one set of rules can be used as a major foundation to follow, while the other could be related to it. This is reasonable and feasible because in this way the modelling process will not be confused all the time and meanwhile both rulebooks are properly taken into consideration and presented. More reasons will be discussed in the next section.

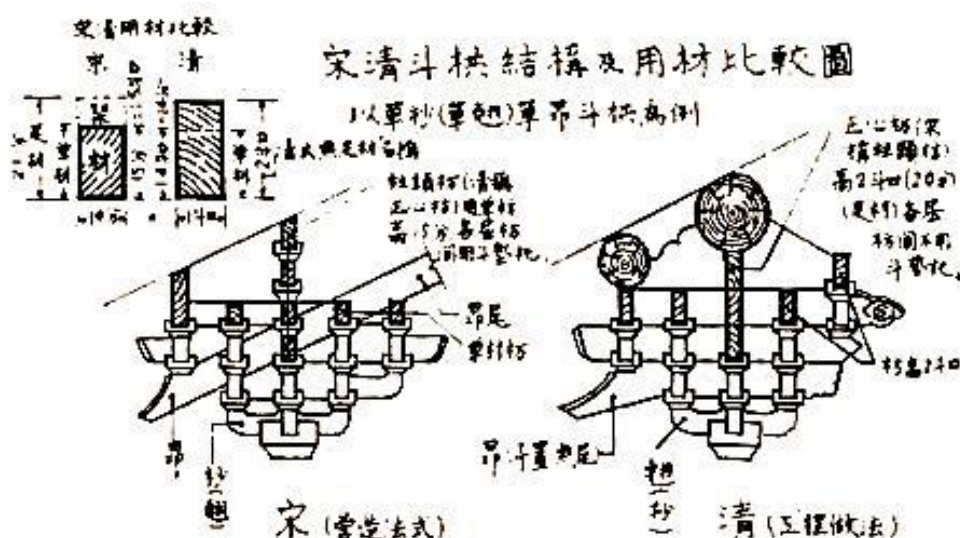


Figure 64. A comparison between Song *dou gong* (left) and Qing *dou gong* (right) (Liang, n.d.)

Third, the width of the beams is increased. In Song Dynasty, the cross section of beams generally has a ratio of 3:2 between depth and width. In Qing Dynasty, this ratio is changed to 5:4 or 6:5. Liang argues that this is “an obvious ignorance of mechanics and the strength of materials” (Liang, 1985). He also points out that “the

overall rule of making the beam two *cun* wider than the diameter of the column seems most arbitrary and irrational” (Liang, 1985). Since the discussion on these rules regarding beams requires evidence from mechanical and material experiments, it is out of the scope of this research. Also as mentioned above, columns are abstractly simplified as circles, lines cylindrical pipes without considering their diameters, shapes and detailed decorations. Given this, the beams in the representations are weakened as illustrations only. Since the beams mainly play the role of structural function rather than a symbolic element in Chinese style, this simplification does not affect the research findings and this can be supplemented in the future.

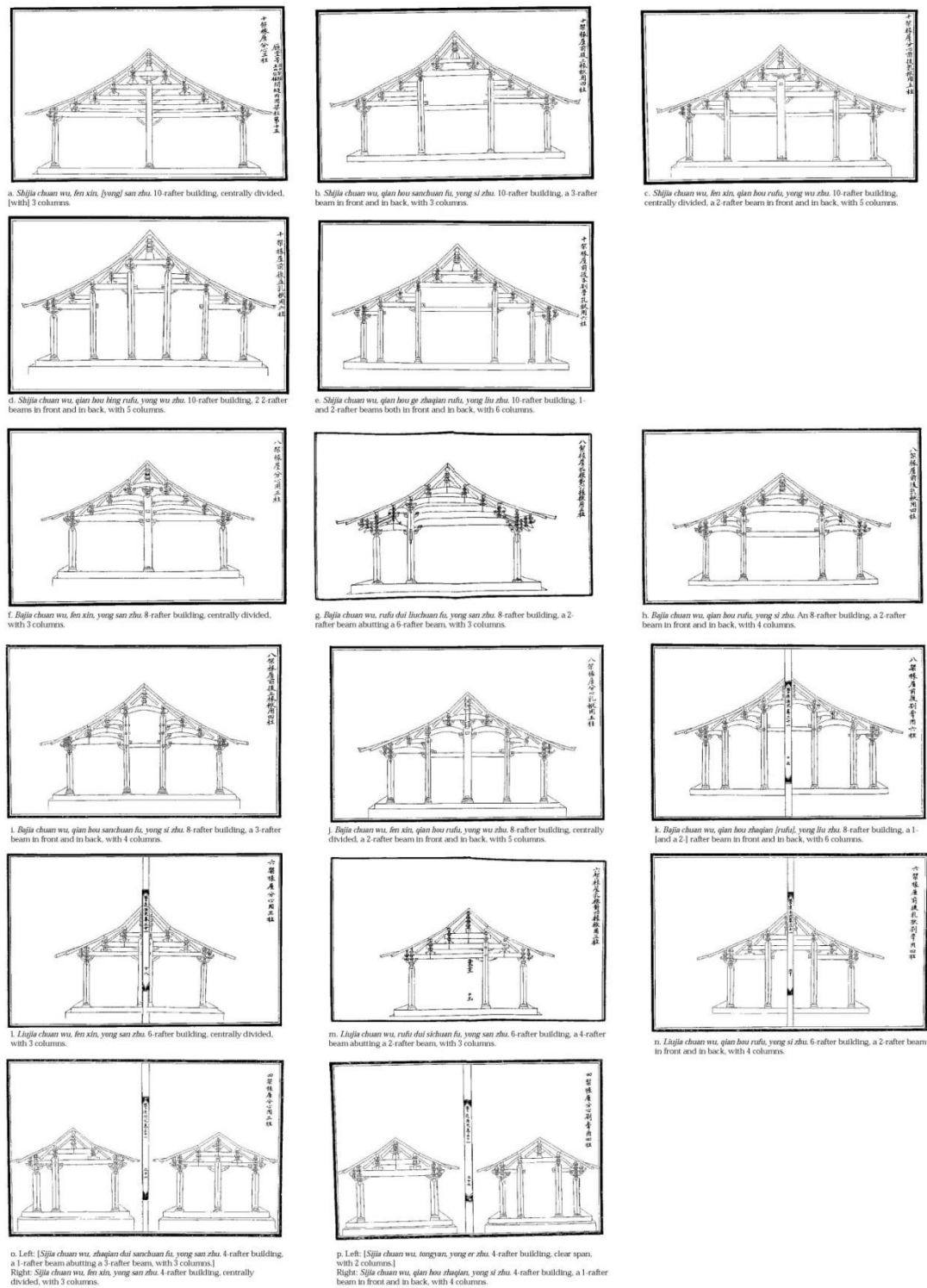
Forth, *Gongcheng Zuofa Zeli* specifies the diameter of a column as six *dou kou*, and its height as sixty *dou kou*, which is ten times of diameters. Given that:

$$6 \text{ dou kou} = 60 \text{ fen} = 15 \text{ fen} (1 \text{ Cai}) \times 4 = 4 \text{ Cai}$$

and the diameter of a column in Song Dynasty never exceeds three *Cai*, the columns in Qing Dynasty is much enlarged. In addition, the shapes and other details of the columns also changed. But again, these will not be included in this research. And the control of the diameter of the columns can be easily supplemented later on.

Fifth, the curved roof in Qing Dynasty seems more or less similar as in Song Dynasty, but the rules behind it are entirely different from those in *Ying Zao Fa Shi*. Details will be discussed in 4.3 of section case study.

Apart from these, Liang makes great contribution in providing considerable drawings of the two rulebooks. For example, a significant work of the *ting tang* sections was carried out by Liang in 1983 in *Ying Zao Fa Shi Zhu Shi* (Liang, 1983, pp. 313-321). It shows the eighteen *ting tang* sections with descriptions on the right corner of the drawings and English descriptions below, as shown in Figure 65. With these works, a deeper and clearer understanding to the rulebooks is achieved and this is the foundation to present the ancient rules algorithmically.

Figure 65. The 18 *ting tang* sections (Liang, 1983)

2.3 Utilisation of the historical references in research

As stated above, *Ying Zao Fa Shi* contributes to both aspects of design guidance and construction quality control. This is an important reason why historical buildings left from the Song Dynasty and afterwards have distinctive and consistent features forming the Chinese style, as well as they can stand firmly for a thousand years until today. On the other hand, similarly as in the Song Dynasty, in contemporary China, there is a lack of the guidance on design and construction in building traditional style Chinese architecture. Although there are “standards of construction and craft in engineering for traditional style architecture” (Liu, 2009), they emphasize the technical skills based on modern technologies, as well as outcome quality control based on contemporary building standards. They are not a real guidance in terms of the design concept and construction process respecting traditional style. Therefore, *Ying Zao Fa Shi* still has its value in a contemporary environment.

As introduced before, this rulebook was published in 1103 but has been lost in the history for a long time until the reappearance of the remaining parts in 1919 and has been republished in 1920 by Qiqian Zhu. But soon scholars found that this 1920 version contained a number of mistakes. “The drawings in particular had suffered considerably from the successive copyings made by scribes who were totally unfamiliar with building techniques” (Fu, et al., 1984). Zhu then decided to correct the mistakes aiming to reconstruct the 1103 edition by setting up a board of scholars to search all the relevant documents in private and imperial libraries. But this was extremely difficult since “many changes in construction methods and shapes and proportions of Chinese architecture had taken place between the Song (Dynasty) and the Qing (Dynasty) but they were not yet known in the early 1920’s” (Fu, et al., 1984). At that time, the board of scholars regarded Chinese architecture as static, which is incorrect as we know now. They believed the palace buildings in Beijing left from Qing Dynasty were exactly the same as those in Song Dynasty. Thus, they tried to unfold *Ying Zao Fa Shi* referring to those Qing Dynasty buildings because those built in Song Dynasty were all burned in 1125. However, they more or less realised this problem shortly because construction details in the remaining parts of the *Ying Zao Fa Shi* were very different from corresponding parts of the Forbidden City in Beijing. But details were far from understood by anyone until the 1930s.

As traditional Chinese architecture is not static, but continuously develops, conventional research method of looking at them one by one as individuals is quite inefficient and even, inaccurate if historical references were partly lost. To overcome this, parametric method is a possible attempt. The changing pace itself is an important relationship between the earlier buildings and later buildings, as mentioned before when rules of two rulebooks are compared. By defining proper boundary conditions, parametric modelling is a powerful tool in understanding such a relationship, and in turn, the development of architecture.

In 1929, Zhu established the Society for Research in Chinese Architecture (*Zhongguo Yingzao Xueshe*) and founded a bulletin. The early volumes of the bulletin published the “secret” handbooks of craftsmen. “Previously, the expert skill of builders had been handed down from master to apprentice, the most respected craftsmen having secret handbooks about their trade” (Fu, et al., 1984). This was expected to be a great help for the scholars’ research of *Ying Zao Fa Shi* since the secret handbooks filled the gap between the knowledge of the scholars and that of the craftsmen. But in fact, “the scholars knew neither the practical aspects of building nor the technical terms and therefore did not understand the handbooks” (Fu, et al., 1984).

This is still a common problem in today’s China that many architects, researchers and students cannot understand the rulebooks very well thus cannot use them and hand them down. This leads to the appearance of many fake Chinese style projects as given in Chapter 1. Therefore, the case studies carried out in this research aims to make the ancient rules understandable and usable in practice, meanwhile fully respecting the rulebooks. Although sometimes minor imperfections are inevitable, this does not affect the creation of the research methodology because as the software develops, the boundary conditions can be defined more accurate and the algorithm could be upgraded all the time. Otherwise, as introduced before, Jie Li himself was an outstanding genius in thousands of year’s history with extremely rich practical experience to produce *Ying Zao Fa Shi*, which current architects and researchers could hardly achieve. And meanwhile, when the rules are not clear enough for the algorithm, extant building examples and craftsmen’s experience will be reasonable references to follow.

In 1931 Sicheng Liang joined the Society, and together with other scholars, started a most fruitful research. This time, they treated *Gongcheng Zuofa Zeli* as a textbook, craftsmen as teachers and palace buildings as teaching material, to study solid knowledge of methods and rules contained in *Ying Zao Fa Shi*. During this process, texts of *Ying Zao Fa Shi* brought them big problems because technical terms were different from the Qing Dynasty, and even, not found in any dictionary. Therefore “they took the corresponding passages in the manual from 1734 (that is *Gongcheng Zuofa Zeli*) as their starting point” (Fu, et al., 1984) and then gradually tried to understand the technical terms in *Ying Zao Fa Shi*. In this sense, *Gongcheng Zuofa Zeli* played an even more important role than its own value, which is, assisting the understanding to *Ying Zao Fa Shi*.

Similarly, this method is borrowed in this research. As compared before, *Ying Zao Fa Shi* is “better” than *Gongcheng Zuofa Zeli* in terms of the systematic description, rule-based concept and detailed level. Also, it is earlier and more influential. Consequently, it is used as the dominant reference in this research. *Gongcheng Zuofa Zeli* is the important complement in assisting the understanding to *Ying Zao Fa Shi*. When building up the algorithm and parametric modelling, the rules described by *Ying Zao Fa Shi* will be the primary consideration. Meanwhile, the rules in

Gongcheng Zuofa Zeli will also be considered in the form of how they are related to the rules in *Ying Zao Fa Shi*. In addition, in order not to be confused, all the terms, names and labels used in this research follow the Song Dynasty system recorded in *Ying Zao Fa Shi*. Most of the names of technical terms have been changed until Qing Dynasty and later on, but this aspect does not affect the research findings thus omitted.

However, even with the help of *Gongcheng Zuofa Zeli*, “much of the content was still obscure” (Fu, et al., 1984) since *Ying Zao Fa Shi* was written in an ancient form of the Chinese language which has no punctuation, different vocabulary, grammar and text direction, not to mention many missing parts, information, drawings and colourings. To overcome this, “fieldwork became the most important activity” (Fu, et al., 1984) in the following years until the early 1980s. During these years, researchers Sicheng Liang, Huiyin Lin, Dunzhen Liu, Zongjiang Mo, Mingda Chen, Daiheng Guo and more, found and carefully measured the only left ancient buildings all across China dated back to 857. Guo even found a *dou gong* on a tomb entry gate tower from about the year 200 B.C. mutually proportional in the same way as described in the *Ying Zao Fa Shi* which indicated that this system may be about two thousand years old (Fu, et al., 1984). All these researchers’ findings contribute a lot to unfold the secret of *Ying Zao Fa Shi*. And their relevant contributions will also be taken into consideration in the case studies.

Up to now, the Chinese language characters have also been changed from traditional type to simplified type (although remain unchanged in Hong Kong and Tai Wan). This presents even bigger problem to modern researchers. But with all the work contributed by previous researchers, together with the digital techniques, a new interpretation under the parametric system towards the ancient rulebooks will be discussed with the aim to reduce the ambiguity and deepen the understanding.

In general, the current version of *Ying Zao Fa Shi* is based on the existing historical documents left from different subsequent dynasties, summarizing influential researchers’ measurement and findings from fieldwork, also including Sicheng Liang’s commentaries and supporting drawings. As stated before, there were three original purpose of *Ying Zao Fa Shi*. In this research, the social class distinction reflected by architecture will not be discussed since it is no longer valid in a contemporary environment. But the grading system (the rule of material) will be covered. Additionally, the constructional rules regarding engineering area will not be discussed although in terms of design aspects will be covered. Most importantly, the traditional Chinese style will be the focus. Nevertheless, this term is a big, complicated and ambiguous concept that there is never a clear, rigorous and unique definition widely and commonly accepted to fully cover this topic. Indeed, it is almost impossible to create such a definition. But interestingly, this concept has existed for a long time and people judge it by all kinds of standards or intuitions given that since 1919, researchers have established a new academic field of Chinese historical architecture with the evaluation of *Ying Zao Fa Shi*. In recent years,

different views of traditional Chinese Style focus on different aspects. In this research, the traditional Chinese style indicates the style consistent with the rules included in the two rulebooks, mainly official buildings, or within the range of data measured from extant historical buildings. This description of the research target will definitely not cover all the aspects included in the concept of traditional Chinese style and could be debateable from different point of views. But this is a reasonable, necessary and feasible boundary.

2.4 Parametric design and Grasshopper on a Rhinoceros

2.4.1 Parametric design

The concept of parametric design, or, parametrics, exists for a long time. “In some design disciplines, like mechanical engineering, they are now the normal medium for work. In others, such as architecture, their substantial effects started only about the year 2000” (Woodbury, 2010, p. 11).

The design of architecture is an iterative process. Therefore, designers require an interface to distribute their ideas. The archetypal medium used to be pencil, eraser and paper. Contemporarily, computer-aided tools are more powerful in building models and visualizing ideas.

“However, the vast majority of these models are still built in such a way that they are difficult to modify interactively. The problem becomes more severe when bespoke 3D models are geometrically complex. Changing one aspect of such a model usually requires extensive low-level modifications to many of its other parts” (Jabi, 2013, p. 9). Taking the traditional Chinese architecture as an example, when integrating all the major timber frame structural components and all the decorative details together, the model of one small civic house could be extremely complex. Since each part closely relates to others, modifications on one part may generate a huge workload on other parts.

To address this problem, parametric design concept is gradually accepted and parametric design software is rapidly developed and frequently used by designers in architecture area now. By this, designers are allowed to specify relationships among various parameters of their models.

Meanwhile, “parametrics is more about an attitude of mind than any particular software application” and the most important requirement is “an attitude of mind that seeks to express and explore relationships” (Woodbury, 2010, p. 1). In other words, the essence of parametrics or parametric design is the relationships: the relationships between different parts of the model, as well as the relationships between the parameters. To build up such relationships, designers not only add and erase

elements (as in the conventional design methods), but also relate and repair them in a coordinated way. During this process, “the act of relating requires explicit thinking about the kind of relation” while “repairing occurs after an erasure, when the parts that depend on an erased part are related again to the parts that remain” (Woodbury, 2010, p. 11).

For example, in conventional method, to design a rectangle means to draw a real rectangle on a piece of paper based on the designer’s idea—how this rectangle should look. And if this shape needs to be changed, the designer would erase it and draw another one. But to parametrically design a rectangle, probably there are at least two options. First, confirm the coordinate of the four points of the rectangle and then connect them by four lines with clockwise or anti-clockwise order. Alternatively, define the mathematical functions that describe the four lines of the rectangle, and then take the intersect points as the four points of the rectangle. In either way, the rectangle is generated by the parametric modelling process. If modification is required, it means the relationships between the lines and points will be re-edited.

From this example, the advantage of such an approach is that when modification or change is required, a designer can “change only a few parameters and the remainder of the model can react and update accordingly” (Jabi, 2013, p. 9). “These derivative changes are handled by the software, but are based on associative rules set by the designer” (Jabi, 2013, p. 9). “With parametric modelling, early design models become conceptually stronger than conventional CAD models and less constrained than building information models” (Woodbury, 2010, p. 2).

In parametric design, the logic of building up the relationships of a design proposal is more important than the proposal itself. “Algorithmic thinking calls for a shift of focus from achieving a high fidelity in the representation of the appearance of a design to that of achieving a high fidelity in the representation of its internal logic” (Jabi, 2013, p. 9).

“In computer science algorithms define the path by which a result is obtained, starting from initial data. The initial data (going into the algorithm) are called input and the results (coming out of the algorithm) output. An algorithm specifies a sequence of steps to obtain a desired result, starting with input data. It is a logical and finite sequence of basic instructions, designed by a human being and carried out by a computer.” (Tedeschi, 2011, p. 15)

With the concept of parametric design and with the algorithms, changes can be efficiently achieved and variations can be generated. This new method has been investigated and applied to a number of contemporary architecture projects. In this research, it will be studied based on a relative new target—traditional Chinese architecture to further explore its application scope in design.

2.4.2 A Grasshopper on a Rhinoceros

Rhinoceros 3D, (usually shortened to Rhino), is a widely used and well-known three dimensional NURBS (Non Rational B-Splines) solid modelling application used in a wide variety of design areas from jewellery to architecture. The main function is “the creation of three-dimensional models based on curves and NURBS surfaces” (Tedeschi, 2011, p. 11). “Rhino is well known for accuracy of the models it produces” (Tedeschi, 2011, p. 11). Compared with other 3D modelling software such as SketchUp, Rhino has strong model analysis capability and has the ability to export data in the formats consistent with digital fabrication machines such as CNC routers and 3D printers. In addition, RhinoScript, a programming language used in Rhino, broadens the ways in which to create and control the design.

“The need for implementing script-based design led McNeel & Associates to develop a “visual” application (visual scripting) based on algorithmic logic, that does not require script writing. This motivation led to the development of Explicit History and also its more recent implementation, Grasshopper; both developed by the Finnish programmer, David Rutten.” (Tedeschi, 2011, p. 12)

Consequently, Grasshopper is a visual editing interface that allows the development of script without programming knowledge. This significant feature suits for the most architects and designers, who do not have a solid programming background. But meanwhile, enables them to think flexibly and develop their design ideas in a computational way.

“By use of an intuitive graphical method based on a nodes interface, the user defines instruction sequences that are converted in three-dimensional models in Rhino’s window. Thus, Grasshopper offers a new way to define shapes by the use of algorithmic modelling.” (Tedeschi, 2011, p. 12).

In this research, the Grasshopper for Rhino is selected as the major software interface in the modelling process as well as in the digital fabrication process. Meanwhile, the feedback for this software based on the investigation of the traditional Chinese architecture will also be discussed in order to further enhance the functional development of such interface in the future.

2.5 Other relevant research

2.5.1 Conventional approach to *Ying Zao Fa Shi*

In the Venice Biennale 2014, there is a group of models of traditional Chinese joint and roof in the roof section of the “Fundamentals” theme and the group of experts

and students also produced part of the content of the book “Roof” (Feng, et al., 2014). There are three most important contributions. First, they translate several essential pages of *Ying Zao Fa Shi* of the major carpentry volume into English. In this way, a wider range of audience will be possible to have a taste to this rulebook. Second, they produce a good illustration to show the major features of the joint and roof parts (see Figure 66). Third, they make a set of 1:1 models to show the size of the eight grades materials, which gives a good understanding to the proportion of the ancient buildings. Figure 67 shows this set of models by making the full material (*zu cai*) of *hua gong* (one of the arms in the joint).

On the contrary, there are also several limitations. First, some of the translations may be confused. For example, *hua gong* (华棋) is translated as “flower arm” as shown in Figure 68. This does not keep the pronunciation as the common translation principle, nor the meaning in Chinese (although sometimes *hua* could mean *flower*, but not necessarily). Sicheng Liang used mainly the pronunciation and at the same time annotated by the meaning when editing his research work. This is a great help for later researchers to easily refer back to the original rulebooks and compare with different research work. Andrew Li once also points out that “it's true that most CAD researchers will not know the difference, but if a reader wants to pursue any of the Chinese references, the information provided will not help them much” (Li, 2015) if they are delivered in a confusing way. In this research, Liang's method will be followed. Second, the illustration shown gives the audience a good taste of how Chinese joint and roof looks like, but does not specify any variation. This brings an impression that the Chinese joint and roof is static and should be exactly in this format. But indeed it contains (in principle) unlimited combinations and variations in design options even only in the Song Dynasty. This is a major problem that conventional methods bring, which does not have the power to show the variations and design options, and in turn, cannot completely reflect the feature of such style. What is more important, if more variations need to be presented, they must be done one by one based on different shapes, consuming labour and time. For the show cases in this exhibition, more than twenty people worked together to provide these products, which is inefficient. Third, a few error gaps are found in details as shown in Figure 69, Figure 70 and Figure 71. In Figure 69 and Figure 70, two gaps on top of *ang* and under *gong* are evident. As introduced before, *ang* is the major mechanical lever playing the important role in joint's function. Such gaps will lead to the failure of the function and meanwhile, is a perfunctory modelling in reflecting its design feature. This does not happen occasionally. A similar gap is also found below *ang* on top of *gong* as shown in Figure 71. Therefore, in general, these may be caused by some minor incorrect representation of the elements of the joint, such as the tenon-mortise of *ang*. This is also a significant problem that a conventional method brings, which is difficult to investigate and prove the complicated and detailed parts. However, digital representation and a parametric method could effectively provide a solution to the second and third problems mentioned above. Details will be shown in the joint case study in Chapter 5. Forth, Figure 72 shows some disconnected parts of

dou and *gong* which were fabricated piece by piece then glued together. These parts should be presented as a whole instead. Considering the joint consists with many elements and all elements are connected by a tenon-mortise method, this kind of presentation easily misleads the accurate interpretation to the elements, as well as does not reflect “the rule of material” regarding the standard grades of the material size. The digital modelling techniques will provide a solution to this problem as shown in Chapter 5.

Apart from these, in the Venice Biennale 2014 there is also a group of models show the contemporary roof types designed by parametric method (see Figure 73) on the contrary to the traditional one. They have very different appearance from the traditional Chinese style and do not show common points at a first glance. So these two groups in the exhibition aim to indicate the difference between parametrics and traditional Chinese style. But in this research, this gap will be bridged by connecting the two aspects instead of conventional point of view by looking at them separately.



Figure 66. The Chinese joint and roof parts in Venice Biennale 2014



Figure 67. 1:1 models of the eight grades material in full material (*zu cai*) of *hua gong*



Figure 68. *hua gong* translated as “flower arm”

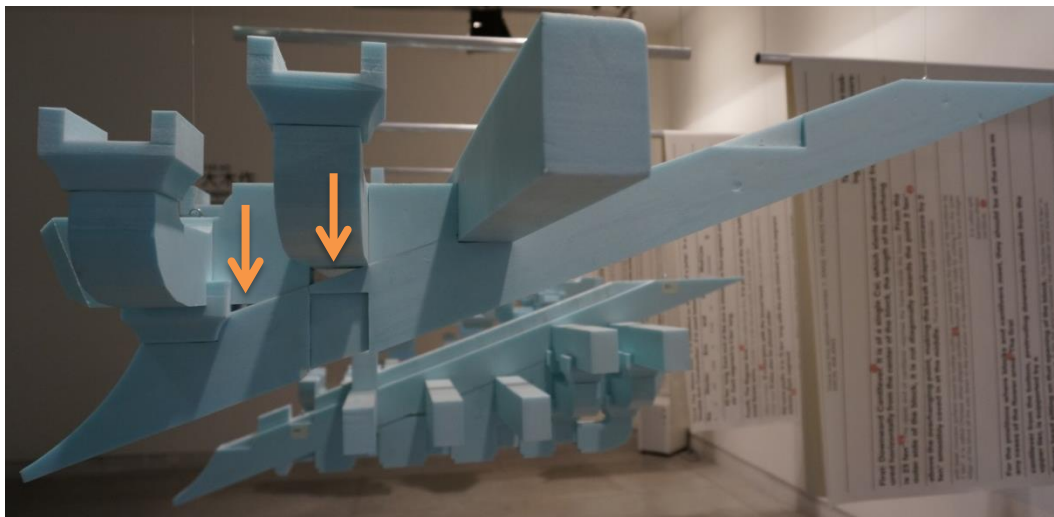


Figure 69. Gaps on top of *ang* under *gong*

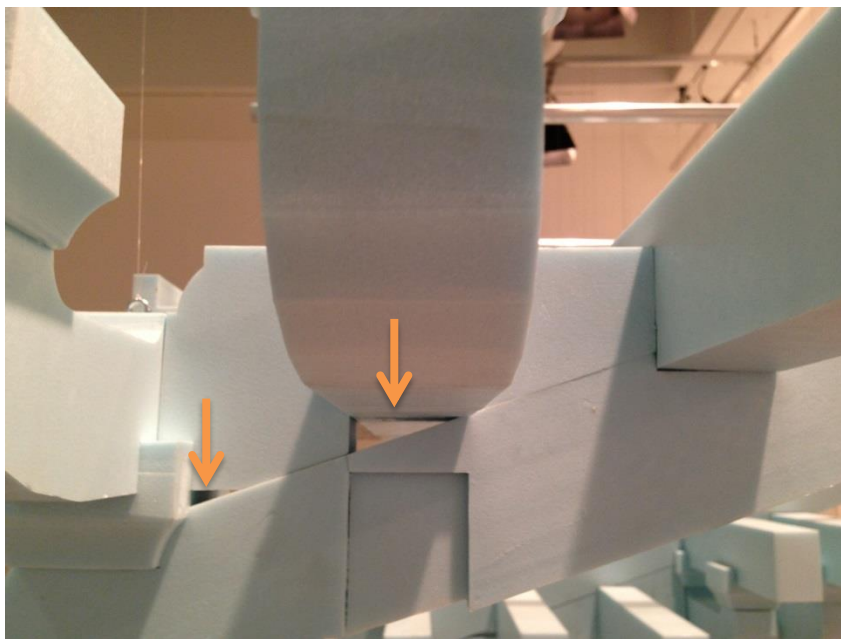


Figure 70. An enlarged picture of the gaps on top of *ang* under *gong*

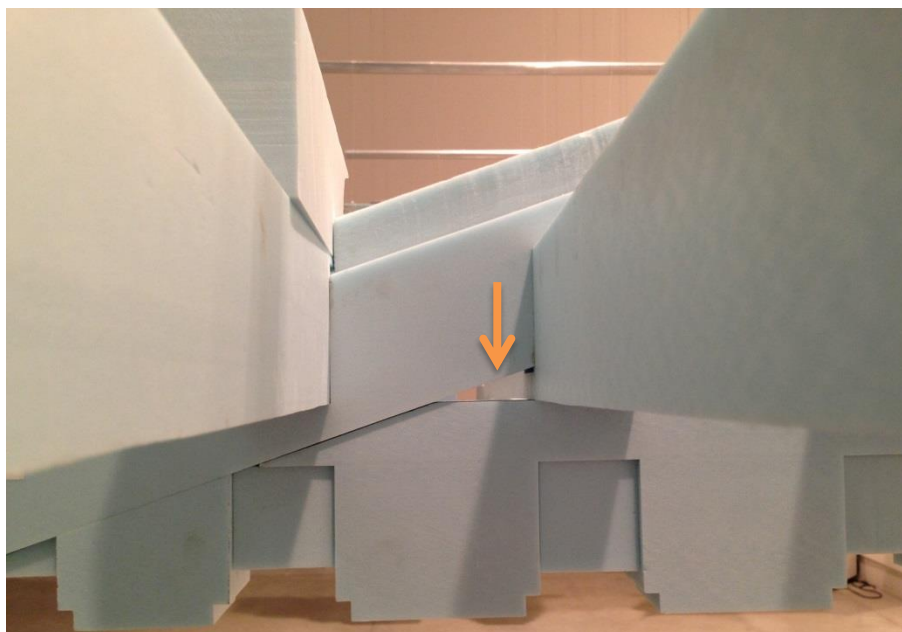


Figure 71. Gap below *ang* on top of *gong*

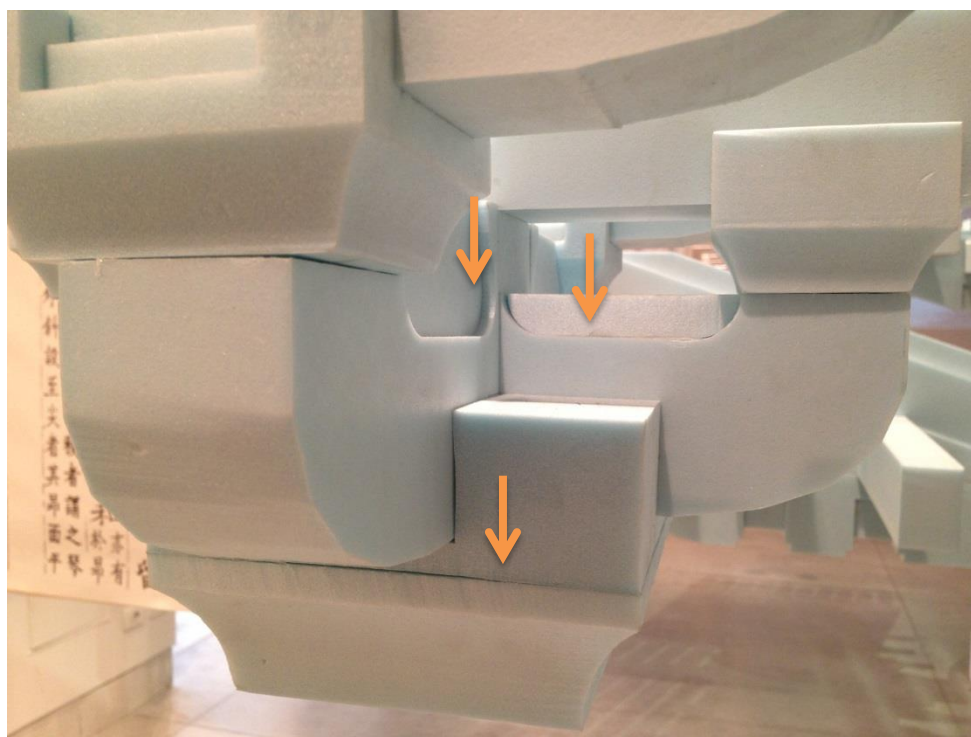


Figure 72. Disconnected parts of *dou* (lower arrow) and *gong* (upper arrows)

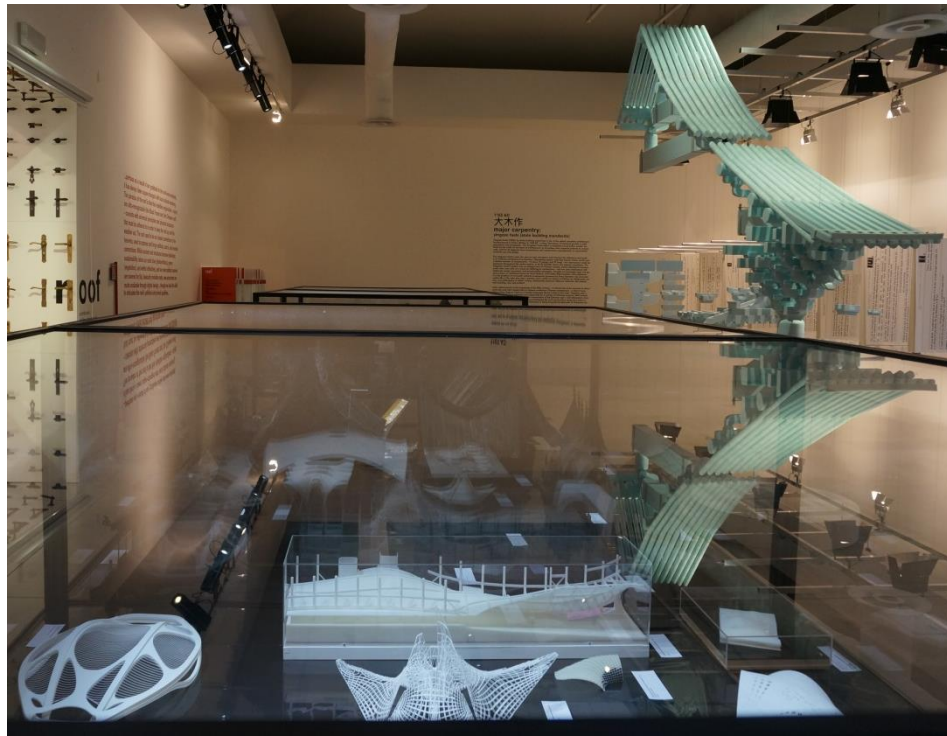


Figure 73. Roof types designed by parametric method

2.5.2 A comparison between Chinese architecture and Western architecture

Regarding “what is the essence of traditional Chinese architecture”, Pu Miao also agrees that this is an ambiguous concept (Miao, 1990). But in Miao’s opinion, Liang’s research to this topic investigates the timber frame structure, *dou gong*, modular system, standard material size as well as relevant constructional methods, which is a superficial investigation to the detailed format rather than concentrating on designers’ design concepts and users’ feeling and impression. Therefore, he summarizes thirteen characteristics of Chinese architecture based on a comparison between Western architecture respectively (Miao, 1990) aiming to explain Chinese style based on people’s feeling and experience. But interestingly, he actually provides a paradox in his principle. On the one hand, he argues that Liang’s research pre-defines the methodology of understanding Chinese architecture the same as utilised in understanding Western architecture—“standardized design and construction” (Miao, 1990) to form a certain style, which is biased. On the other hand, he makes his own argument based on the comparison between the two, which means he tries to find out Chinese features corresponding to those existing in Western architecture. Even, his conclusion of Western architecture’s feature such that “standardized design and construction” might be narrow and incomplete. Additionally, his research basis of people’s feeling and experience is very subjective,

which makes it difficult to produce a convincing conclusion. Consequently, Miao's opinion has been strongly debateable.

Given that in the early 1990s, digital techniques were not commonly used in research on Chinese architecture, the limitations in Miao's research was accepted since the lack of advanced technology limited his understanding that through the proper algorithmic representation, design concepts can be reflected on the format, and format (or the style) integrates the design concepts. They are not two separate aspects, but the link could be the digital techniques. This reflects the first research value that better interprets the Chinese style. In addition, to understand traditional Chinese style, the comparison is not necessarily based on Western architecture style, instead, could be based on Western or contemporary technology. This is the second values of this research that to have a better understanding of the function of the digital techniques. Finally, Liang's research of a systematic approach based on rulebooks and practical data towards the Chinese style has its advantage as discussed before. Therefore, the study on the Chinese style cannot jump out from this foundation and purely relies on people's subjective feeling, although this could be a useful supplement to the formal digital representation. Consequently, in this research, three case studies will be carried out first and the applications, including a survey collecting people's subjective feeling and how the research findings assisting people in design, will be a supplementary part to support this research, as shown in Chapter 7.

2.5.3 Pattern language

“Back in 1977, the book *A pattern language* first introduced the concept of people designing buildings for themselves, and guaranteeing the comfort and functionality of the buildings they designed, because the elements of the language are "patterns", elements which are a collective memory of things which work in our surroundings.” (Center for Environmental Structure , n.d.) There are 253 patterns that form a language, which defines towns, buildings and communities (Alexander, 1977). From these patterns, people can choose different details and combinations to create their own design, and even get infinite results. This is very practical and thus “has been widely accepted by building contractors and do-it-yourself homeowners” (Bhatt, 2010). Meanwhile, this has similarity with the Chinese rulebooks in terms of assisting people in creating new designs, although the rules are different from the patterns. In addition, the pattern language could also be understood as a form of algorithm in parametric ideas at the early stage, which generate different outcomes.

However, there is still the difference between generative design and intelligent design. Initially parametric modelling was referred to as generative, and some people still agree this now. But it is aware that strictly speaking this kind of software-based parametric modelling process should best be described as intelligent rather than generative. In generative software the outcome is not known, where as in parametric software the outcome is controlled. More specifically, the controlled outcomes

reflect the rules in ancient rulebooks. And through this way, the tradition is well understood and respected.

2.5.4 Shape Grammar approach to *Ying Zao Fa Shi*

Developed in the 1970's by Stiny and Gips (Gips, 1975) (Stiny, 1980), Shape Grammar has been widely used in research. It has three key components: initial symbols, design rules and final designs. The design rules act on the initial symbols and get the final designs. Following each typical set of rules will result in one corresponding final design. Thus Shape Grammar generates a language of design. The initial symbols that are rewritten are the same symbols that occur in the final design. And the symbols that are rewritten are geometrical entities (for instance: line segments) rather than discrete symbols. The earliest Shape Grammars worked with line segments, but extensions were developed that deal with colour and with three-dimensional shape.

Figure 74 shows an example of Froebel's building blocks generated by shape grammar (Stiny, 1980). Initial small blocks acted by the rules of spatial relationships and stacked. The outcomes are different building blocks.

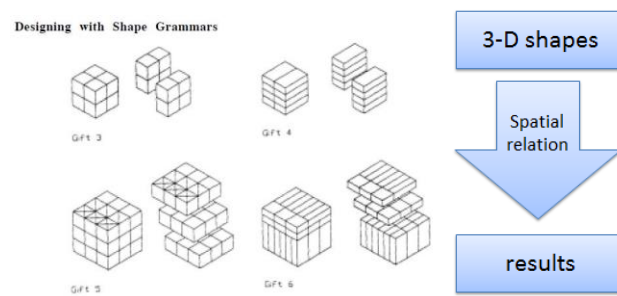


Figure 74. An example of Froebel's building blocks generated by shape grammar (left) (Stiny, 1980) and the author's summary of its concept (right)

Andrew Li has used Shape Grammar for traditional Chinese architecture, which is “a formal method for creating designs” (Li, 2003). Using his principles, the process begins with an initial design, then is transformed repeatedly by applying design rules to it, resulting in a final design. Figure 75 shows an example of his work on *ting tang* section. What the final design is depends on how and in what sequence the rules are applied. The rules and the initial design make up a grammar, and the set of designs that can be created with a grammar is the language of designs, or a style. In his work, the constructive rules are based on *Ying Zao Fa Shi*. The rules described in this book have been formalised, generalised and applied to both natural languages and artificial

languages such as computer programming and, together with the re-organisation and re-creation, finally becomes the new product. From his research, it is assumed that the traditional Chinese architecture follows a series of rules and orders in its structure. Therefore, Shape Grammar also has its sequence when develop the final design. Li's research mainly concentrates on floor plan, section and roof, which are the basic and major structure to define Chinese style. Similarly, these aspects will be covered in the case studies in this research in order to have a better comparison between the two methods, as well as find out the linkage.

Although after hundreds of years, the architecture in Qing Dynasty has changed compared with those in Song Dynasty, it is still an optimistic expectation that during the whole historical period a set of parametric rules could be derived from all dynasties. Li's work is mainly based on *Ying Zao Fa Shi*, but of course, as introduced before, any research work of *Ying Zao Fa Shi* should refer to *Gongcheng Zuofa Zeli*. However in this research, the rules in *Gongcheng Zuofa Zeli* could be considered as a certain relationship to the rules in *Ying Zao Fa Shi*. In other words, the rules in *Gongcheng Zuofa Zeli* independently exist, and at the same time, they can be integrated into the algorithm based on *Ying Zao Fa Shi*.

Li does not include *dou gong* as his key research target. But in Wu's work, the Shape Grammar approach to it has been discussed (Wu, 2005). Especially, the sequence of constructing a *dou gong* could be used as an effective method in teaching as shown in Figure 76. This is an important foundation to understand such a complicated structure, but again, a Shape Grammar approach does not have the power to show all the variations, and in turn, is weak in reflecting a style. Also, the lack of software support makes it difficult in practical design. Therefore, in recent research, more people start the analysis to a certain target by Shape Grammar, then develop the presentation into parametric modelling. In this research, *dou gong* will also be covered, and investigated under the parametric environment.

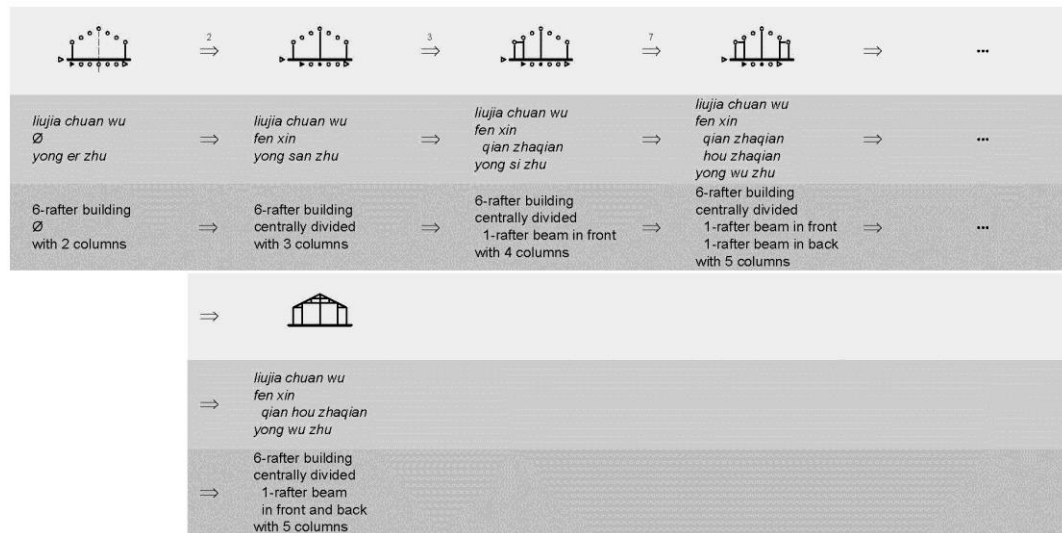


Figure 7. Derivation of a 6-rafter *ting tang*, centrally divided, 1-rafter beam in front and in back, with 5 columns. We apply rules 2, 1, and 7 to establish the distinctive features. We omit the process of cleaning up the labels and descriptions. It is shown in figure 8, redrawn as in the *Yingzao fashi*.

Figure 75. An example of Andrew Li's work on section by Shape Grammar approach (Li, 2003)

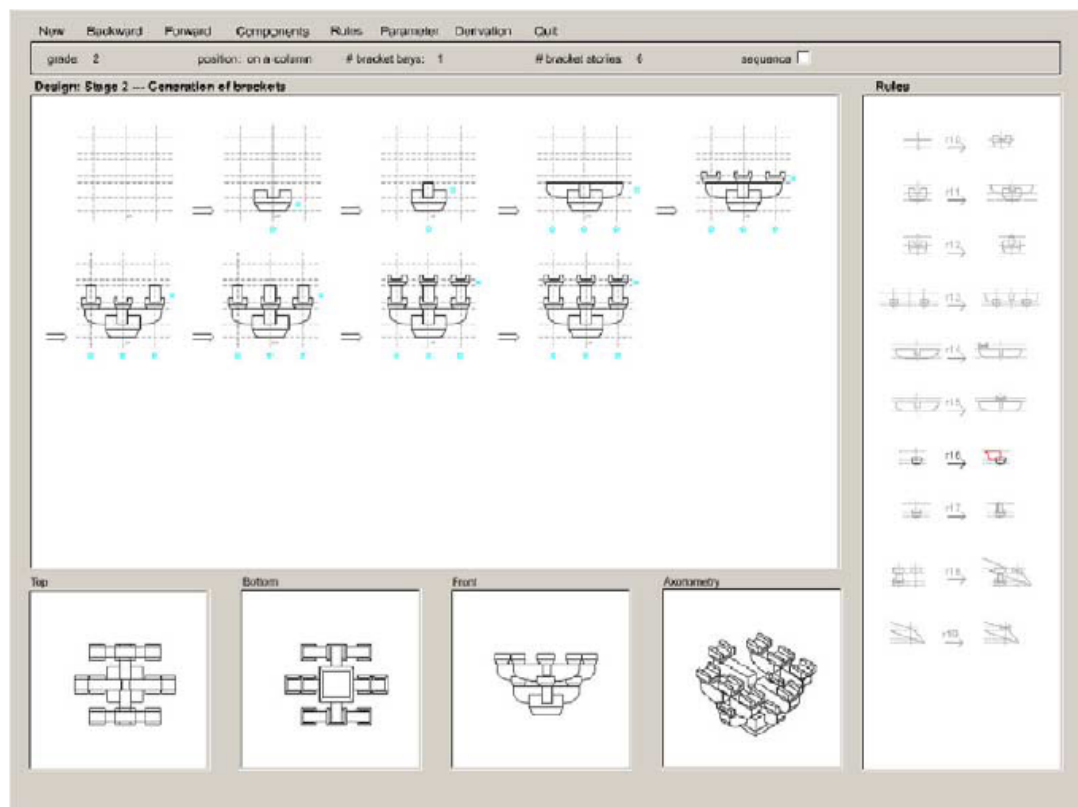


Figure 76. An example of Wu's work on *dou gong* by Shape Grammar approach (Wu, 2005)

2.5.5 Research of proportion on traditional Chinese architecture

In 2011, a series of research findings of the proportion and scale of the traditional timber frame architecture was published based on the study of *Ying Zao Fa Shi* and measurement data of extant buildings (Wang, et al., 2011). In this research, Wang tries to build up a system to describe the proportion and scale for traditional Chinese architecture, corresponding to Western classic architecture principles. Wang follows Liang's methodology of using Western analysis method on Chinese architecture, and creates his analysis principles evaluating Chinese features. Meanwhile, Wang also refers to *The Ten Books on Architecture* by Vitruvius Pollio on the topic of the proportion and scale. Therefore, this research illustrates how Western principles could be applied to Chinese topics. But different from Miao's research as mentioned before, although the Western principles are borrowed, Wang concentrates on the Chinese features of proportion and scale, reflecting the ideas recorded in *Ying Zao Fa Shi*. Thus, the method of applying Western principles to Chinese architecture, especially to the study of *Ying Zao Fa Shi*, is a good inspiration for this research. Wang provides case studies on floor plans, sections, elevations, multi-storey buildings and decorations, which widely cover the features of traditional Chinese architecture. But since his research does not aim to create parametric representation, his contributions may not be proper to use as an algorithm for modelling. Instead, his findings reflect more about the features of design results, which is equivalent to the outcome product in parametrics.

Apart from these, Wang points out some weak points of *Ying Zao Fa Shi*. For example, "*Ying Zao Fa Shi* lacks the summary on the overall proportion of the buildings" (Wang, et al., 2011). Wang mainly solved this problem by using the measurement data from extant buildings, and by checking and comparing data of different buildings in order to prove his principle. While in this research, such kind of omitted summaries on different aspects will be given based on attempted digital modelling. Additionally, Wang's measurement data will be referred to as an evidence to check the correctness of the modelling process.

2.5.6 Digital representation of the Yuanming Palace

Since 2000 until 2012, a project of digital representation of the Yuanming Palace was carried out in Tsinghua University during the 12 years' time with the contribution of many researchers. This is a relatively large scale research in the digital heritage area in recent China. Yuanming Palace was a magnificent royal palace and garden in the Qing Dynasty but was destroyed in the Opium War in 1860. In more than a century, people have long wished to see it as it would have been in its

heyday. In this project, with the digital representation, a number of rendering effect images are produced to show such scene of its heyday (see Figure 77 as an example), leaving audiences a deep and vivid impression of how it looked.

There are three main aspects in the methodology of this research. First, research of the historical references, including historical documents and similar extant examples, were carried out as a basis for the digital representation (see Figure 78 and Figure 79). Second, the heritage site was investigated, in order to build up a completed database. Third, the digital modelling and virtual assembly process took place to get the final representation. From their research findings (Guo & He, 2012), this methodology is proved to be reasonable and effective. Given this, such methodology is valuable in the area.

However, their research aimed to represent an individual architecture, rather than a style. In other words, they tried to find all kinds of evidence to rebuild a certain destroyed architecture, and only this piece (or set) of architecture. Their work has less effect on summarizing a style of a longer period and formed by different pieces of architecture. Therefore, in the research of this thesis, their first aspect will be partially borrowed, with a concentration on the ancient design rules. Their second aspect, that is, the measurement data from the sites, will be considered as a verification of the parametric models in this author's research.

In addition, their research is more close to a narrative demonstration of this masterpiece. They mainly produced descriptive texts, ancient drawings, as well as nice rendering effects, which form a good reference for the general public. Nevertheless, from the information they provided (Guo & He, 2012), it is insufficient for other researchers to re-analyse their work, nor for designers to use in practice. Also, comparing the amount of people and time they spent on this project, and the research outcomes, the inefficiency of their digital modelling process is indicated. And this problem does not only happen in their research. Trying to digitally build up each complicated building one by one would result in an immense workload. And without understanding of the style (or, so-called rules, regulations, patterns), fragmented information takes a long time to resolve. While in this research, these problems will be taken into consideration to seek better solutions.



Figure 77. A rendering effect image of the Yuanming Palace (Guo & He, 2012, p. 141)

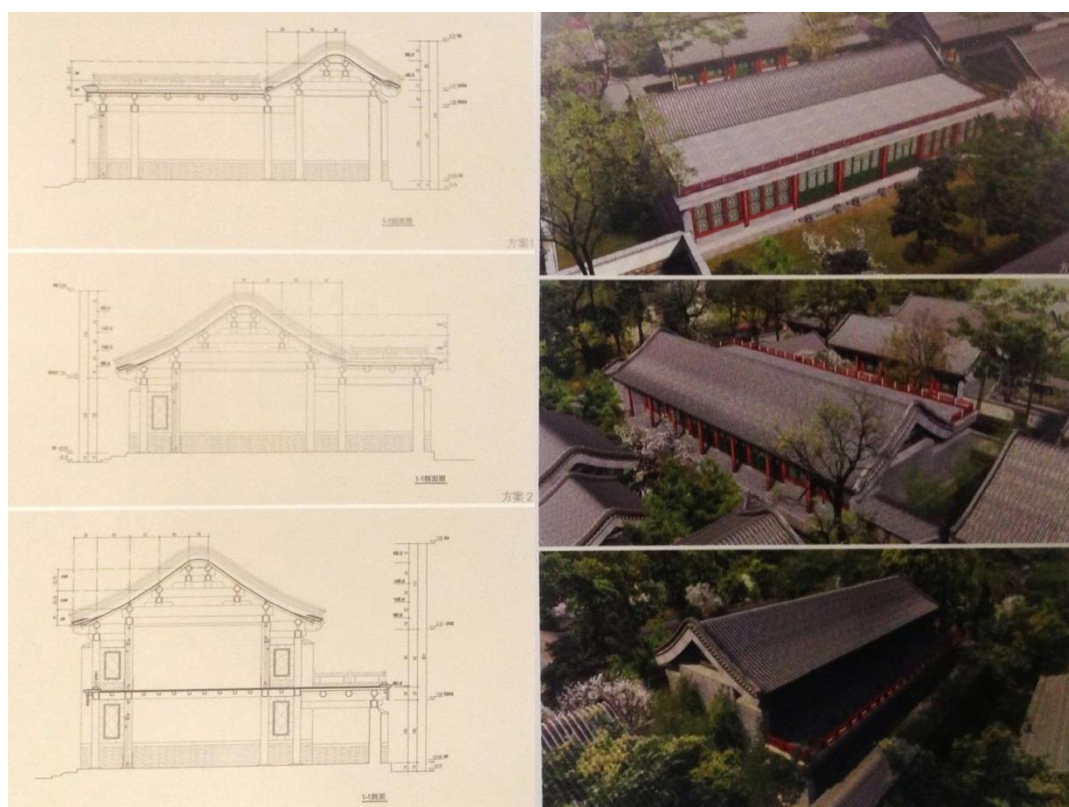


Figure 78. Qinghui Pavilion section diagrams (left) and its digital rendering images (right) (Guo & He, 2012, pp. 122-123)



Figure 79. Extant stone lion of the Summer Palace (left) and digital rendering stone lion of the Yuanming Palace (right) (Guo & He, 2012, pp. 34-35)

2.5.7 Digital fabrication of Japanese joint

As introduced in Chapter 1, traditional Japanese architecture has its roots in traditional Chinese architecture and they share many similarities in style and technology. In the modern period, there is more influential research on the Japanese architecture which are internationally accepted. For example, the traditional Japanese joint has the similar concept of the tenon- mortise technology in traditional Chinese architecture. There is a case study aiming to digitally fabricate the Japanese joint (Tugite and Shiguchi, see Figure 80) and rediscover its value in the era of digital fabrication (Kanasaki & Tanaka, 2013). In their research, they review the joint technology by looking at its basic shapes and functions. Then a parametric technique is used in the process of changing the basic shapes (as shown in Figure 81). After this the CNC milling machine and 3D printer are used to produce the final products. This is a good example showing how digital fabrication is applied to help to maintain the traditional skills usually involved by craftsmen, and meanwhile how traditional values refine and benefit the advanced technology. In their research, parametric modelling process is only used as a visual display tool to control the output shapes for the fabrication process. But the function and value of parametric technique is far more than the shape controlling. In the three case studies and applications of this research, the deeper meaning that parametrics can present will be discussed.



Figure 80. Japanese wood joint (Kanasaki & Tanaka, 2013)

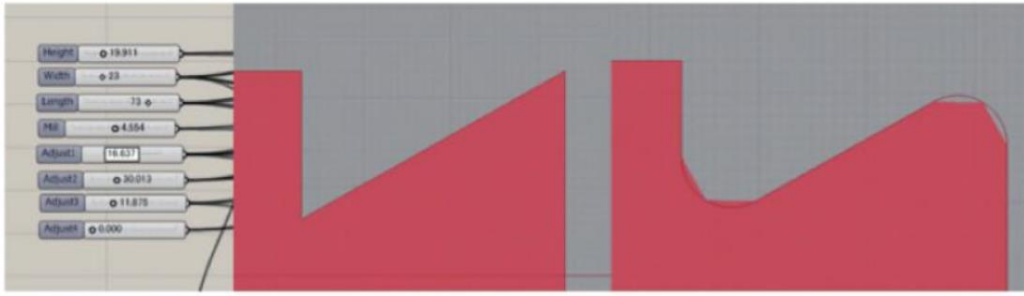


Figure 81. Shape change for CNC milling machine (Kanasaki & Tanaka, 2013)

2.5.8 Parametric approach to *Gulou*

Apart from these, a successful case study of the *Gulou* structure building located in southwest China by shape grammar and parametric modelling has been demonstrated by Xiong (Xiong , et al., 2013). *Gulou* is a type of building used by minority ethnic Dong people in China. In this case study, the design and construction knowledge of such building type was investigated in details by shape grammar and then parametric modelling based on the grammar was tested and applied to explore the performance of *Gulou*, as shown in Figure 82. After this, the possibility of the new designs generated by the parametric rules was discussed, as well as the educational function brought by this case study. Finally Xiong also suggests that, this could be a starting point for the long term study of the *Gulou* building techniques and implication to the contemporary architecture (Xiong , et al., 2013). It is worth learning from this case study that the parametric modelling plays an important role in heritage studies, adding to the conventional method in this area. Meanwhile, the new research target also brings parametrics new opportunity to attempt on different style and form of architecture other than contemporary buildings, and upgrade this technique by solving challenges in the process.

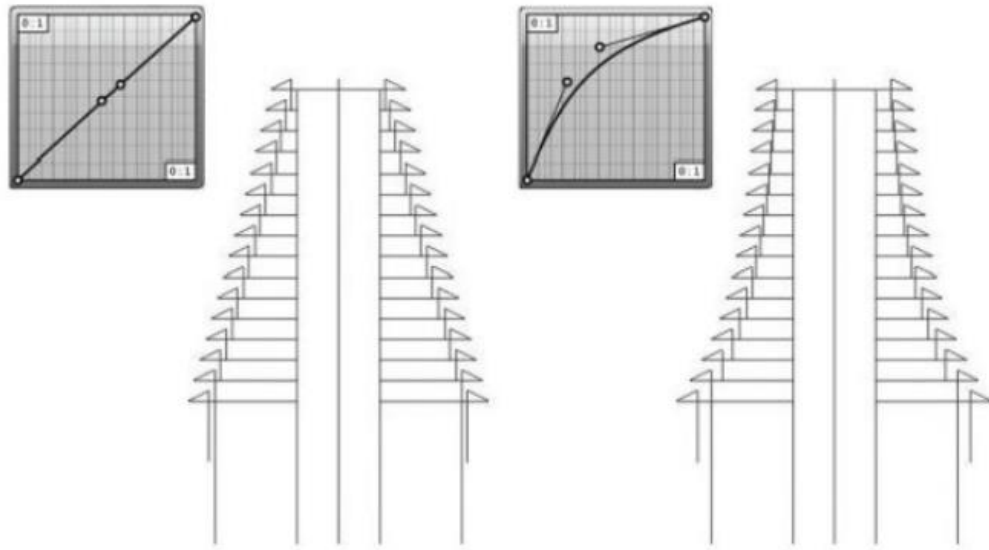


Figure 82. Parametric modelling of the *Gulou* (Xiong , et al., 2013)

In addition, in practice, parametric techniques are providing architects with an alternative to the traditional tools which adds to the conventional mode of adding and removing marks (Woodbury, 2010). On the other hand, parametric modelling, introduces a fundamental change: individual marks and objects could be related and changed together in a coordinated way. So far, architects could not only add and erase, but also relate and repair a group of elements together efficiently. Parametric systems used to play a significant role in engineering disciplines, such as operating rectangular table of cells rather than a design, but now, it is an attempt for it to be treated as a tool for design.

Chapter 3 Case study 1—floor plan

This chapter looks at generation of the floor plan based on *Ying Zao Fa Shi* and other relevant references. A series of rules and hypotheses are reviewed before the generation of the floor plan models using Grasshopper and Rhino. In the modelling process, several attempts are undertaken in order to optimise the algorithm and output result. The models are discussed and evaluated by checking with the measurement data of the extant buildings. Additionally, the comparison with parallel research of the Shape Grammar approach will be discussed in Chapter 8.

In *Ying Zao Fa Shi*, there is not a specific volume introducing the rules of the floor plan, making it an initial difficulty for the case study. Although in the diagram volume there are a few examples of the floor plan, there is no relevant or valuable information about those diagrams. From the very limited number of diagram examples, no summary can be made for the algorithm. Instead, at the beginning of the major carpentry volume, “the rule of material” based on *Cai* (this word in Chinese means material) is introduced firmly. The reasons for this have been described in previous chapters.

However, in this research, the floor plan is selected as the first case study, for the following two reasons. First, from a research perspective, although there is no concentrated information about the floor plan in *Ying Zao Fa Shi*, it is possible to collect sufficient information and summarise a set of rules. As a basis in architecture design, the floor plan is closely related and connects other parts. As a result, when introducing other parts in the rulebooks, relevant information of the floor plan can be obtained in *Ying Zao Fa Shi*. (And oppositely, when modelling other parts of a building, the floor plan is non-negligible.) Together with Sicheng Liang and other people’s research work, it is believed that although the size and scale of the floor plan was changing continuously in the ancient dynasties, the style and pattern, in other words, the basic design concept and rules remained quite stable. Therefore, *Gongcheng Zuofa Zeli* and extant buildings play an important role in support of summarising the rules as well. Second, from a design perspective, in order to use the research findings in practice, the floor plan is applicable as a starting point in the contemporary design habit, rather than beginning with the very abstract concept of “the rule of eight grades of standard timber material”. Once the traditional style and rules can find a path to be used and accepted in the contemporary environment, it can then be revived and passed down.

In addition, since the floor plan is not isolated, the relationship with the section is also taken into consideration at an early stage in this chapter, aiming to well prepare for the next case study.

3.1 Description of the ancient floor plan system

In order to understand and recreate floor plans, a description of the ancient floor plan system is necessary. Based on *Ying Zao Fa Shi*, the following factors can be used to describe a building. First, the building type, such as *dian tang* or *ting tang* (here *tang* means hall, *dian tang* is the large scale halls usually used in upper level buildings, *ting tang* is the small scale halls used in lower level buildings, but sometimes a mixture exists). Second, the overall dimension (measured in modular units). Third, building width (and bay width). Fourth, building depth (and rafters). Fifth, the level of the building, in other words, the grade of the material which the building should use (and this is also used to calculate the absolute value of the modular unit).

In ancient China, there were many variations of the floor plan. Figure 83, Figure 84 and Figure 85 shows the single building types, combined building types and courtyard types consist of single and combined buildings respectively. Regarding single building types, there are mainly two types: rectangular shapes and non-rectangular shapes. These two basic types compose the combined building types. And further, they compose the courtyard types and group of buildings. Among all these buildings, the rectangular shape is the basic and most commonly used type. Its variations show logic regulations that could form a set of the rules. Therefore, the type of rectangular shape is the modelling target in this chapter. In comparison, the non-rectangular shapes are less commonly used and are lacking in regulations. There are several non-rectangular floor plans, which includes the use of the triangle, circle, sector, octagon, polygon, and the superposition of polygons and Wan (万) shape. They are widely used in pavilions and gardens which typically appear in Southern China. But these irregular shape floor plans are not discussed in this thesis.



Figure 83. Single building types (Liu, 1984, p. 15)

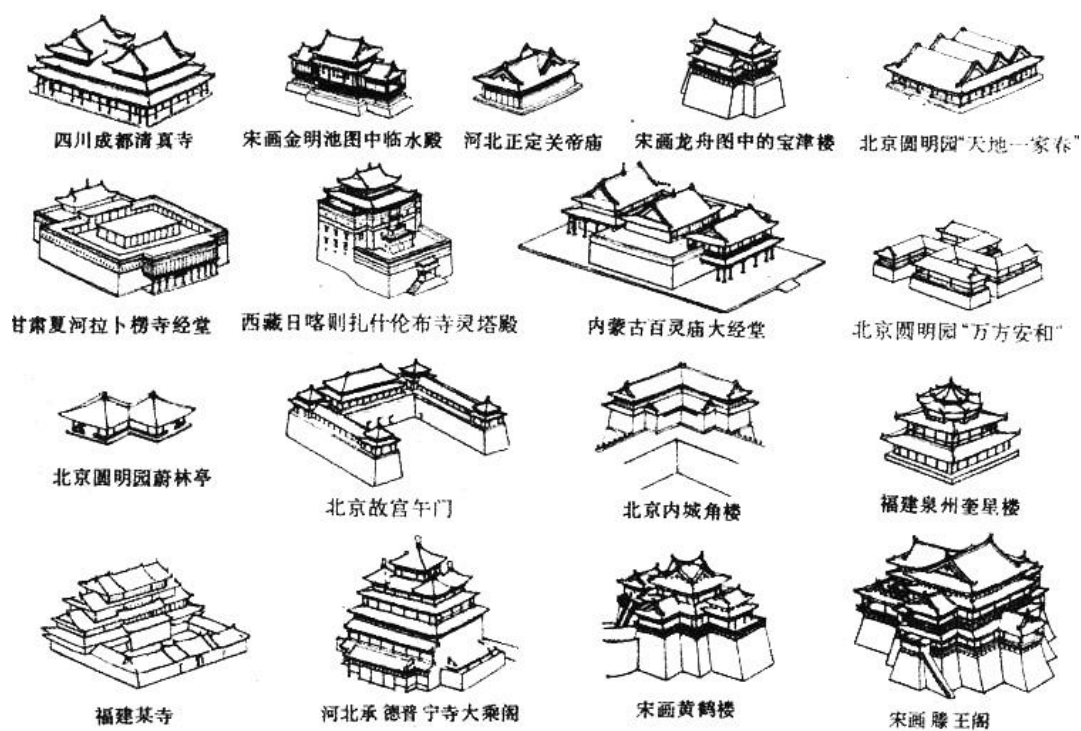


Figure 84. Combined building types (Liu, 1984, p. 16)

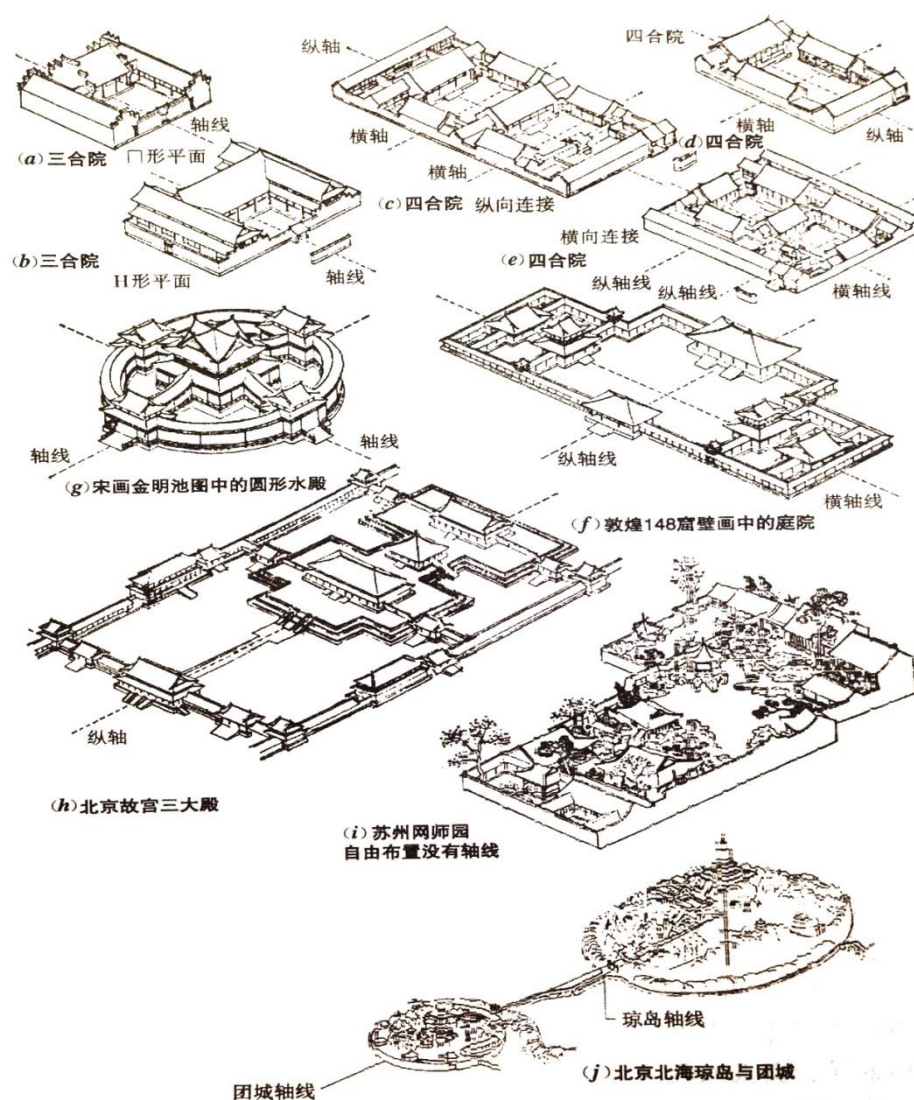


Figure 85. Courtyard types consist of single and combined buildings (Liu, 1984, p. 12)

3.2 Rectangular shape floor plan

In the rectangular shape cases, the floor plan of a single building consists of two major factors: building width and building depth, which determines the dimension and scale of the building. The building width and building depth form the area of a building. This area can be divided into small units (small rectangles), which are called bays (in principle, each bay could have four columns at the four corners, although not in every case). Each bay is determined by the bay width and bay depth, as shown in Figure 86. The sum of the bay width or bay depth gives the building width or building depth. But in reality, the bay depth is not described in the set of parameters as above. Instead, the horizontally projected rafter is used to measure the depth of a bay. The definition of rafter is shown in Figure 87, as the distance between the two red horizontal lines is called one rafter. Rafter is frequently used both when

describe the depth and when describe the beam. There are three reasons why bay depth is replaced by rafter. First, *Ying Zao Fa Shi* mentions for *ting tang* type building, one bay depth equals to two rafters deep but it does not mention the relationship for the *dian tang* type building. Therefore in order to unify the parameters in the later parametric modelling, the rafter is selected as the depth measurement for both building types. Second, to be consistent with the next case study on the section, the rafter is a key parameter in defining the section. The rafter is closely related to the disposition of the columns and the total number of columns. Third, from the craftsmen's experiences, they tend to use rafters rather than bay depth in practice. Consequently, the four major parameters to describe the floor plan are: bay width, number of bays, rafter, and number of rafters. The formulas presenting the relationships of these four parameters are shown in Figure 88.

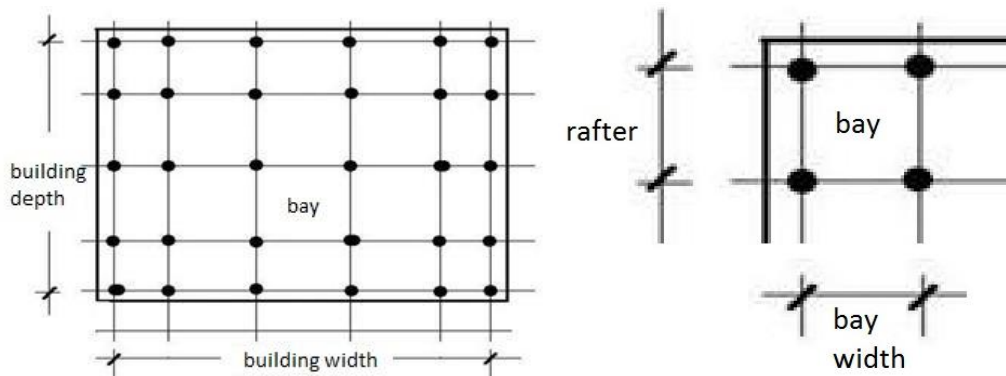


Figure 86. Factors of the floor plan

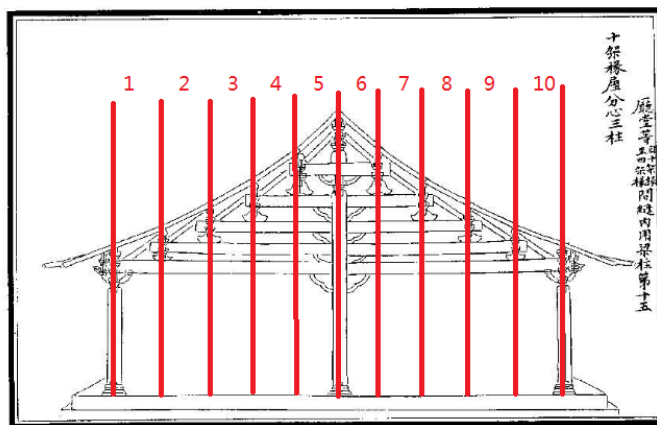


Figure 87. The definition of the rafter numbering—an example of a ten rafters building, original drawing done by Liang (Liang, 1983)

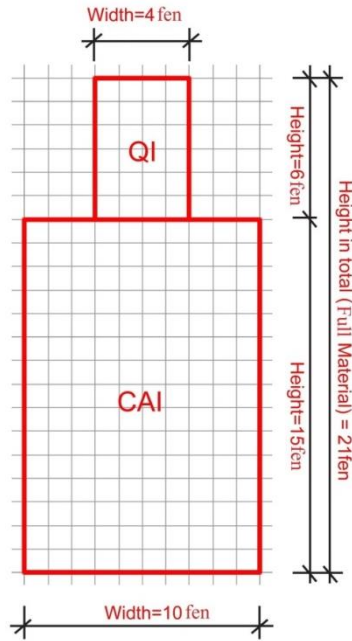
$$\begin{aligned}
 \text{building width} &= \sum_{\text{number of bays}} \text{bay width} \\
 \text{building depth} &= \sum_{\text{number of rafters}} \text{rafter length}
 \end{aligned}$$

Figure 88. Formulas of the floor plan factors

3.3 Utilisation of *Cai* and measurement units for floor plan

The significant concept of *Cai* and “the rule of material” was introduced in section 1.1.1.1 when introducing the Tang and Song Dynasties. Followed by this, it was discussed again in section 2.2 and shown in Figure 61 how to measure the eight grades of *Cai*. Then in section 2.5.1 the 1:1 scale models of the eight grades of *Cai* was shown in Figure 67. Here (and also in the following case studies), this concept and its application in algorithm will be further discussed in detail.

Recall the description before, “the rule of material” is to set “the rule of eight grades of standard timber material (called *Cai*)” as a standard to distinguish building levels. As shown in Figure 89, it is the section view of the standard timber material, which is applicable for all the eight grades, but in eight different sizes (absolute values) for eight grades. If the definition of *Cai* from section 2.2 (Liang, 1985) is reviewed, the term *Cai* has a twofold meaning. First, it is a standard-sized timber used for *gong*, or the “arm” of the *dou gong*; and all timbers of the same depth and width. Here in Figure 89, in order not to confuse ourselves with the “depth” in the term “building depth”, and more intuitively get the meaning from the figure (usually use “width” and “height” in section view), the “depth” used in Figure 61 (and used by Liang) has been changed to “height”. And “height” will be kept using as the parameter name in the modelling process. Second, *Cai* is a modular unit for measurement. Examples are shown in Figure 90. Note, usually *Qi* cannot exist independently, therefore the number of *Qi* is either equal to or smaller than the number of *Cai*. The absolute values then can be calculated depending on the eight grades of *Cai*.

Figure 89. Standard timber material (called *Cai*)

$$\begin{aligned}
 1 \text{ Zu } Cai \text{ (full material)} &= 1 \text{ Cai} + 1 \text{ Qi} \\
 2 \text{ Zu } Cai \text{ (full material)} &= 2 \text{ Cai} + 2 \text{ Qi} \\
 &\vdots \\
 1 \text{ Zu } Cai \text{ (full material)} + 1 \text{ Cai} &= 2 \text{ Cai} + 1 \text{ Qi} \\
 2 \text{ Zu } Cai \text{ (full material)} + 1 \text{ Cai} &= 3 \text{ Cai} + 2 \text{ Qi} \\
 &\vdots
 \end{aligned}$$

Figure 90. *Cai* as a module for measurement

As shown in Figure 89, the height of each *Cai* is divided into 15 equal length, and the width of the *Cai* is divided into 10 equal length, each length is called *fen*. Every measurement in the building, for example, the height and breadth of the building, the dimensions of every member in the structure, the rise and curve of the roofline, can be measured in terms of *fen*. Then based on the grade of the *Cai*, *fen* can be converted into absolute values as well. When two *Cai* are used one above another, a block of six *fen* in height, called *Qi* is customary to cushion them by filling the gap. One set of measuring consisted by one *Cai* and one *Qi* in height is called a “Zu *Cai*”, means full material. Figure 89 also shows the dimension of *Qi*, which is 6 *fen* in height and 4 *fen* in width. The measurements and proportions of a building in the Song Dynasty are expressed based on the rules above. The use of modules of *Cai* and

Qi is a basis and an essence to derive the algorithmic presentation and in turn, a significant part in parametric modelling. Consequently, the four major parameters to describe the standard timber material are: *Cai* width, *Cai* height, *Qi* width, *Qi* height. And the formulas are shown in Figure 91.

$$Cai \text{ width} = 10 \text{ fen}$$

$$Cai \text{ height} = 15 \text{ fen}$$

$$Qi \text{ width} = 4 \text{ fen}$$

$$Qi \text{ height} = 6 \text{ fen}$$

$$Zu \text{ Cai (full material)} = 21 \text{ fen}$$

Figure 91. Formulas of the standard timber material

Next, the eight grades of the *Cai* need to be clarified. Once the level of the building (could be based on the owner's social class or the function of the building) is confirmed, the grade of the standard timber material should be used for this building is then determined. In other words, the dimension of the *Cai*, *Qi* and *fen* could be obtained and converted into absolute values. Then the whole set of the components of the timber structure is also determined based on these rules.

Depending on the eight grades of the buildings, a *fen* can have eight different absolute values (Liang, 1983), measured in *cun* (a Chinese length unit in ancient period), as shown in Figure 92. From the table, although originally the length of *fen* is also distinguished by different building types, indeed the building types do not affect the result. And the grade is the only variable in determining the length of *fen*. Therefore, the table can be simplified, as shown in Figure 93.

length of <i>fen</i> (in <i>cun</i>)	0.60	0.55	0.50	0.48	0.44	0.40	0.35	0.30
Grades of <i>dian tang</i>	1	2	3	4	5			
Grades of <i>ting tang</i>			3	4	5	6		
Grades of other types						6	7	8

Figure 92. Absolute values of *fen* for eight different grades and different building types

Grades	1	2	3	4	5	6	7	8
length of <i>fen</i> (in <i>cun</i>)	0.60	0.55	0.50	0.48	0.44	0.40	0.35	0.30

Figure 93. Absolute values of *fen* for eight different grades

Based on the formulas in Figure 91, the four major parameters of describing the standard timber material can be calculated, as shown in Figure 94.

	<i>Cai</i> width	<i>Cai</i> height	<i>Qi</i> width	<i>Qi</i> height
Grade 1	6.00 <i>cun</i>	9.00 <i>cun</i>	2.40 <i>cun</i>	3.60 <i>cun</i>
Grade 2	5.50 <i>cun</i>	8.25 <i>cun</i>	2.20 <i>cun</i>	3.30 <i>cun</i>
Grade 3	5.00 <i>cun</i>	7.50 <i>cun</i>	2.00 <i>cun</i>	3.00 <i>cun</i>
Grade 4	4.80 <i>cun</i>	7.20 <i>cun</i>	1.92 <i>cun</i>	2.88 <i>cun</i>
Grade 5	4.40 <i>cun</i>	6.60 <i>cun</i>	1.76 <i>cun</i>	2.64 <i>cun</i>
Grade 6	4.00 <i>cun</i>	6.00 <i>cun</i>	1.60 <i>cun</i>	2.40 <i>cun</i>
Grade 7	3.50 <i>cun</i>	5.25 <i>cun</i>	1.40 <i>cun</i>	2.10 <i>cun</i>
Grade 8	3.00 <i>cun</i>	4.50 <i>cun</i>	1.20 <i>cun</i>	1.80 <i>cun</i>

Figure 94. Absolute values of the standard timber material for eight different grades

In the Song Dynasty, 1 *chi* = 10 *cun* = 309~ 329 mm (the exact value is debateable). So 1 *cun* = 30.9 ~32.9 mm. Based on Liang (Liang, 1983) and commonly used value, take that 1 *cun* = 32 mm approximately for this research, the final absolute values in the international unit then can be obtained. For example, if the building is in Grade Three, 1 *fen* = 0.5 *cun* x 32 mm/*cun* =16 mm. The four values of the standard timber material are: *Cai* width =160 mm, *Cai* height = 240 mm, *Qi* width = 64 mm, *Qi* height = 96 mm. Although here the approximate value that 1 *cun* = 32 mm is directly used, this value can be easily changed if later more evidence proves it should be replaced by a more accurate value. This does not affect the algorithm of the modelling process using the modular units and the function of calculating the final absolute value remains the same. Only one number in the formula needs to be replaced and the output results can be updated. This is one of the advantages of the parametrics.

3.4 Parametric models of the floor plan

In order to build up the parametric logic, the four major parameters of the floor plan need to be clarified: the value of bay width and rafter, and number of both, which constitutes the building width and building depth. Unfortunately, at this stage, *Ying Zao Fa Shi* does not provide a systematic definition. Instead, it gives information partially by defining and partially by enumerating. Despite this, the parametric model could still be built up by first making hypothesis based on the information in hand and then evaluating with the diagrams in the rulebook and extant building measurement data. Later in section 7.1, a survey of a set of selected floor plans generated parametrically will be discussed in order to further support the findings

here, which reflecting a subjective point of view of the audiences. Applications will be shown in the rest part of Chapter 7.

The assumptions here are mainly based on the investigation of architectural historians Mingda Chen (Chen, 1993), Sicheng Liang (Liang, 1983) and contemporary research done by Andrew Li (Li, 1997). As shown in Figure 95, the four parameters are summarised. In particular, the bay width is not given directly. The calculation is as follows: a bay has two sets of *dou gong* (the bracket joint) that sit on each side of the columns (the black dots in Figure 86) and either one or two sets between the columns (intercolumnar *dou gong*). The centre-to-centre distance of *dou gong* is $125\text{ fen} \pm 25\text{ fen}$. Thus the bay width with one intercolumnar *dou gong* is $250\text{ fen} \pm 50\text{ fen}$, and with two intercolumnar *dou gong* is $375\text{ fen} \pm 75\text{ fen}$. Therefore the total range of bay width is 200—450 *fen*. In addition, the centre bay is often wider and in most extant examples the two outer bays are often slightly narrower than the others (Li, 1997). In the table, the modular unit *fen* is used and the absolute values could be calculated by the functions in the parametric modelling and exported directly.

	<i>ting tang</i>	<i>dian tang</i>
Building width (number of bays)	3,5,7,9 bays	3,5,7,9,11 bays
Building depth (number of rafters)	4,6,8,10 rafters	2,4,6,8,10,12 rafters
Bay width	200-450 <i>fen</i>	
Rafter	$\leq 150\text{ fen}$	

Figure 95. Definition of the four parameters

3.4.1 Attempt 1—basic model

After all the parameters are clarified, the parametric model now can be built. Figure 96 shows the logic diagram for the parametric modelling. In this logic diagram, *ting tang* and *dian tang* types are integrated together since Liu (Liu, 1984) points out that “although *Ying Zao Fa Shi* distinct the two types strictly, buildings are slickly dealt with in practice”. From extant examples, this analysis is proved. Some buildings show the character in between *ting tang* and *dian tang* types, such as Fengguo Temple Main Hall. Some buildings are combined by both *ting tang* and *dian tang* types, such as Shanhua Temple Main Hall. Some buildings are under the catalogue of one type, but meanwhile replace one or a few characters belong to another type, such as Shanhua Temple Sansheng Hall. And some buildings are hard to define which type they are. This phenomenon does not only happen to the floor plan, but are also common when later look at the section case study. Therefore, when the two types of

the buildings share the same rules in modelling process, they will be integrated together to consider. When they use different rules to present, they will be distinguished and in this case, the building type will also be a parameter to consider (this will be discussed in detail in Chapter 4). In addition, as mentioned above and shown in Figure 92 and Figure 93, building types do not affect the calculation of the modular unit *fen* and in turn do not affect the final absolute values. Consequently, to integrate both together is efficient and has no impact on the accuracy in the floor plan case study.

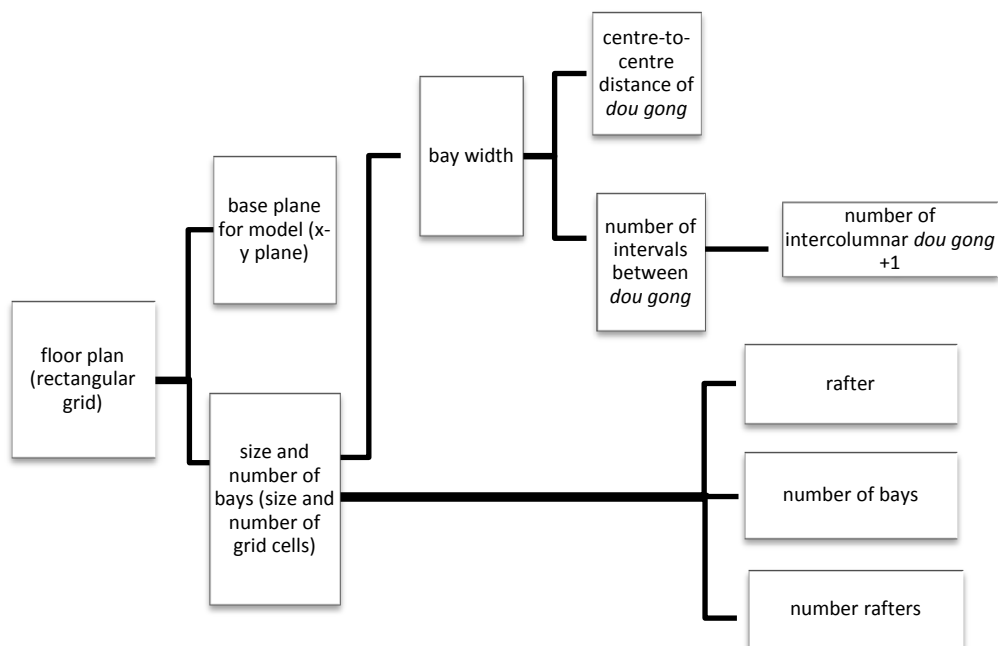


Figure 96. Parametric logic diagram

To understand the afterwards Grasshopper interface diagrams, a reader may refer to the official web site (www.grasshopper3d.com) which is a starting point to learn Grasshopper, from the meaning of the various sliders and nodes to the connection logics, from the algorithms of basic geometries to the use of complex mathematical functions. It is also a gateway to different online resources, plug-in updates, discussions and examples by other users, to enable further study this software.

The rectangular floor plan grid is set first by defining the x-y plane as the base plane. The next step is to define the size and number of bays. In order to achieve this, the four parameters described above are outlined here. As the primary parameters, the rafter, number of bays and number of rafters can be directly controlled by the corresponding number range listed in Figure 95. The bay width is a multiplication of two factors: centre-to-centre distance of *dou gong* and number of intervals between *dou gong*. Additionally, the number of intervals between *dou gong* is equal to the

number of intercolumnar *dou gong* plus one. Since the number of intercolumnar *dou gong* is known directly, finally the bay width can be calculated. Thus, overall, there are five parameters that can be controlled, as shown in Figure 97. In addition, there is one judgment in this algorithm: the building width should always be larger than the building depth. And if so, the conclusion will appear true, as shown in Figure 98. Under this one set of algorithm (see Figure 99) the floor plan of both *ting tang* and *dian tang* types of building with commonly used number of bays and rafters are involved.

Take Figure 99 as an example to introduce the Grasshopper interface. There are five basic parameters, controlled by five sliders. They are calculated by “addition” or “multiplication” functions to get the numerical results. Then the results are imported as inputs of a rectangular plane. The output will be the floor plan diagram shown in Rhino. If any value of the basic parameters is changed, the output diagram will be automatically updated. To make sure the total width is always larger than or equal to the total depth, a “true or false selection” function is used to compare both values.

Figure 100 to Figure 103 show examples of the variations. In order to clearly indicate the variations, in each figure, only one parameter is changed and all the other parameters are remained unchanged.

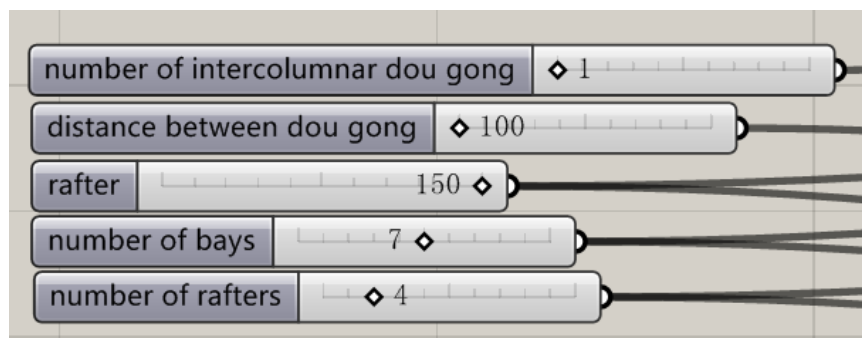


Figure 97. Attempt 1 parameters

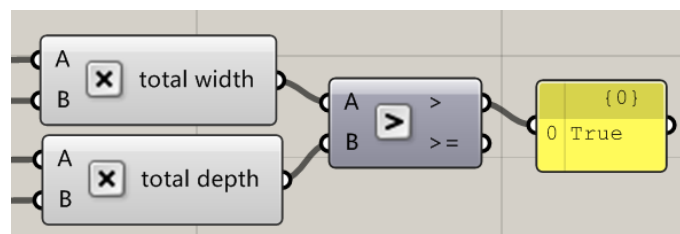


Figure 98. Attempt 1 value judgement

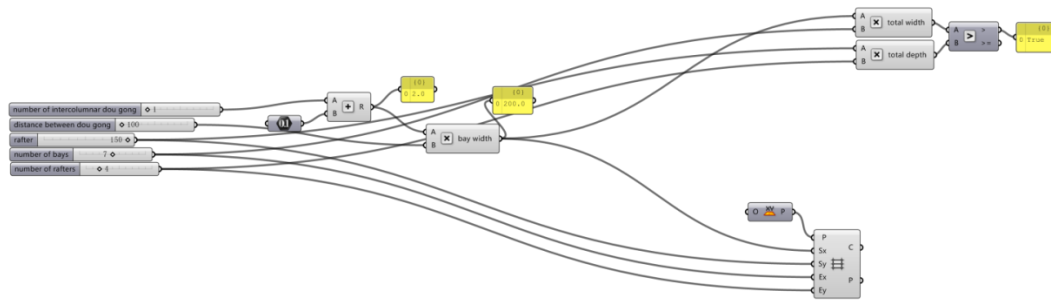


Figure 99. Attempt 1 modelling process



1 bay



3 bays



5 bays

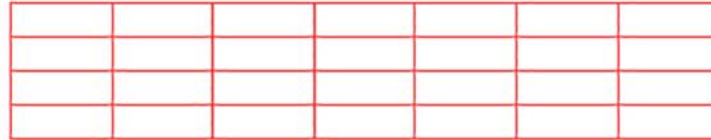


7 bays

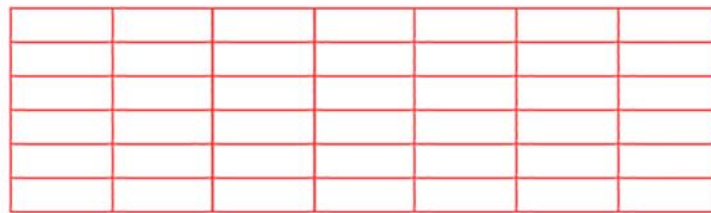
Figure 100. 1—7 bays, 2 rafters floor plan examples (variable: number of bays)



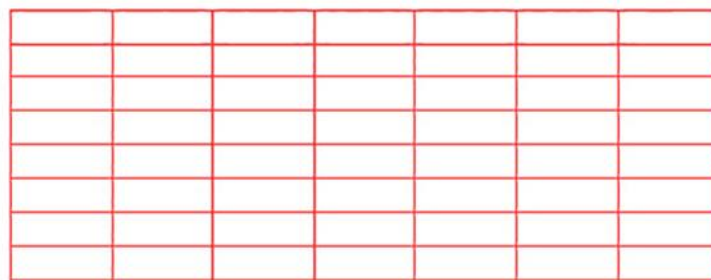
2 rafters



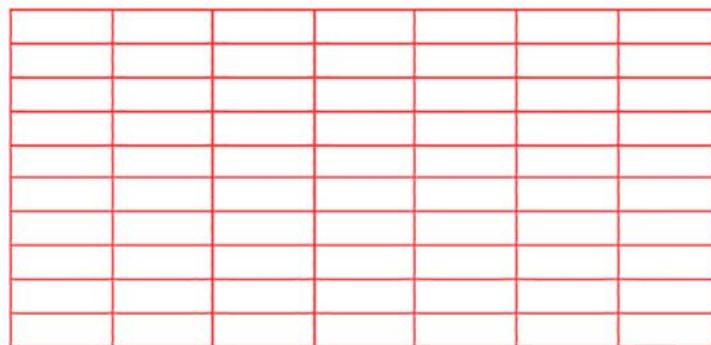
4 rafters



6 rafters



8 rafters



10 rafters

Figure 101. 7 bays, 2—10 rafters floor plan examples (variable: number of rafters)

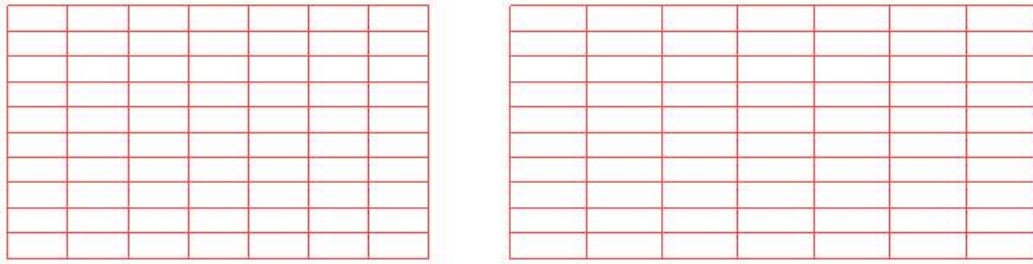


Figure 102. 7 bays, 10 rafters floor plan examples (variable: bay width)

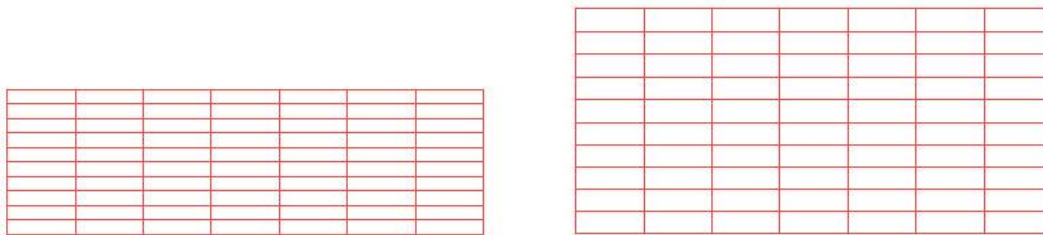


Figure 103. 7 bays, 10 rafters floor plan examples (variable: bay depth)

3.4.2 Attempt 2—connection with *Cai*

In attempt 1, the basic model is built up. In this attempt, the important concept—*Cai* will be taken into consideration of the modelling. First of all, to present *Cai* and export the values, the parametric model of the standard timber material is built based on the rules and definitions described in section 3.3 and shown in Figure 89 and Figure 91. The modelling process is shown in Figure 104. And the grade 1 to grade 8 models of the standard timber material are shown in Figure 105. Since from now on the algorithm will become more complicated and the grasshopper panel will be full of components, in order to keep a clear logic, components belong to one group or present one part of the model will be grouped together and made as a cluster. The cluster of *Cai* is shown in Figure 106. Based on Figure 94, the absolute values of the standard timber material for eight different grades can be calculated. But as mentioned before, the calculation can be made by function during the modelling process and the output will show the result. Figure 107 shows an example of the output of the parameters of *Cai* for grade 3 material. And all the eight grades of material's measurement data (converted into absolute values) can be obtained by controlling the input grades.

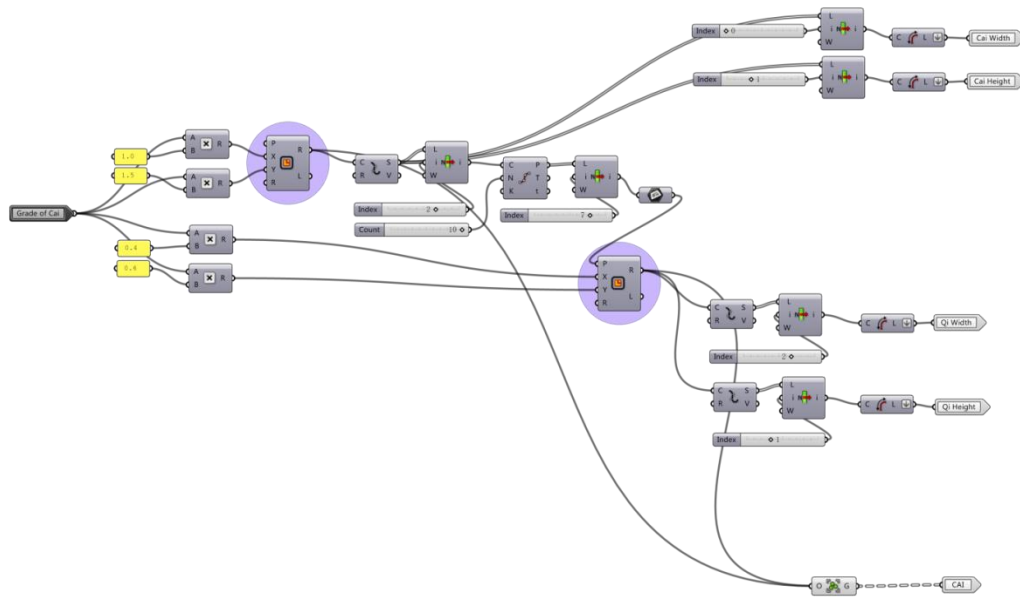
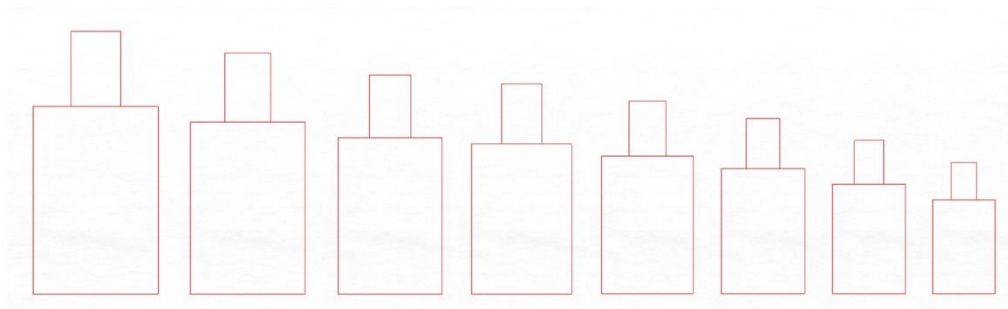
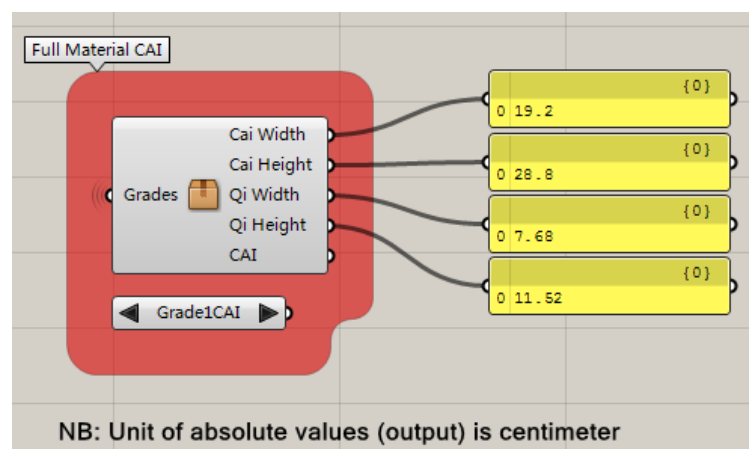
Figure 104. Modelling of the standard timber material-- *Cai*

Figure 105. Grade 1 to grade 8 models of the standard timber material

Figure 106. Cluster of *Cai*

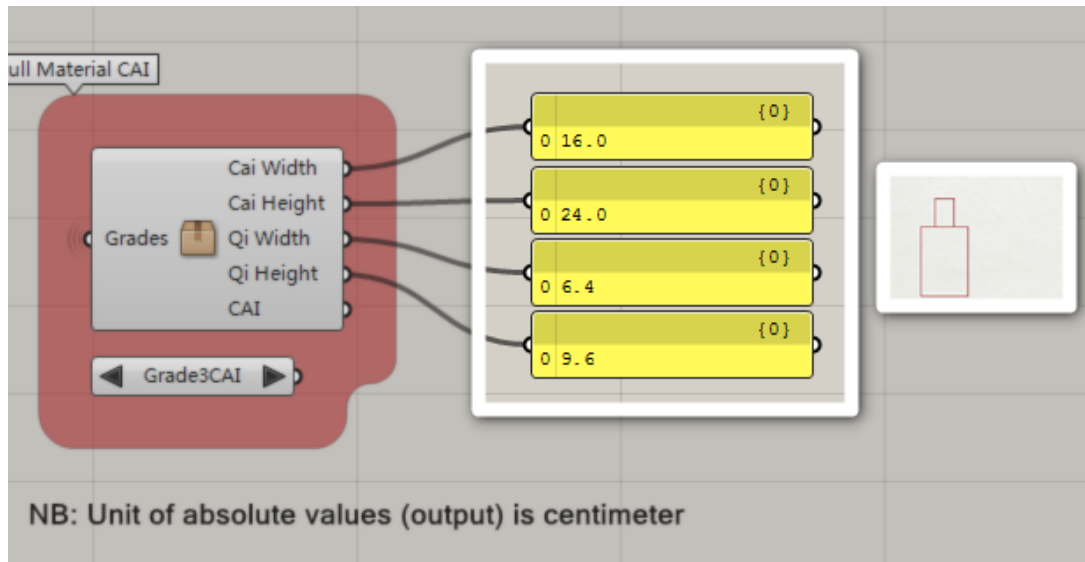


Figure 107. An example of the output of the parameters of *Cai* (Grade three)

In this attempt, the five parameters used in attempt 1 are reduced to four parameters as input control to build the floor plan. They are bay width, rafter, number of bays and number of rafters, as shown in Figure 108. This can be achieved by optimising the algorithmic functions within the cluster. Additionally, the modelling part of *Cai* is connected to the basic floor plan model, as shown in Figure 109. Thus, in addition to the variations of the bays, the floor plans in all the eight different grades can be presented now. Examples of different grades floor plans are shown in Figure 110. Apart from these, the building width and building depth can also be obtained as outputs, as shown in Figure 111. This is useful if the measurement data of extant buildings need to be checked and compared with the parametric model.

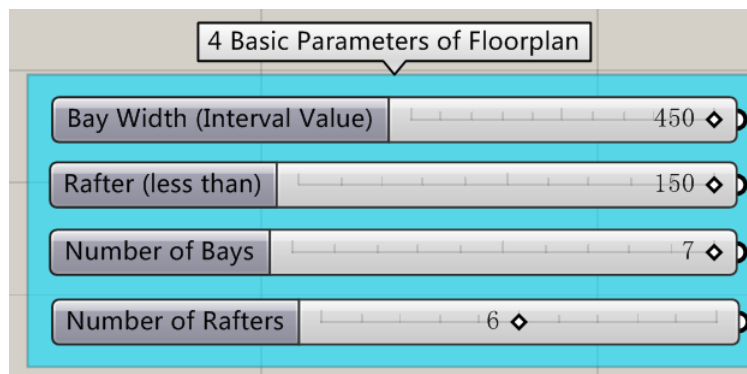


Figure 108. Attempt 2 parameters of the floor plan

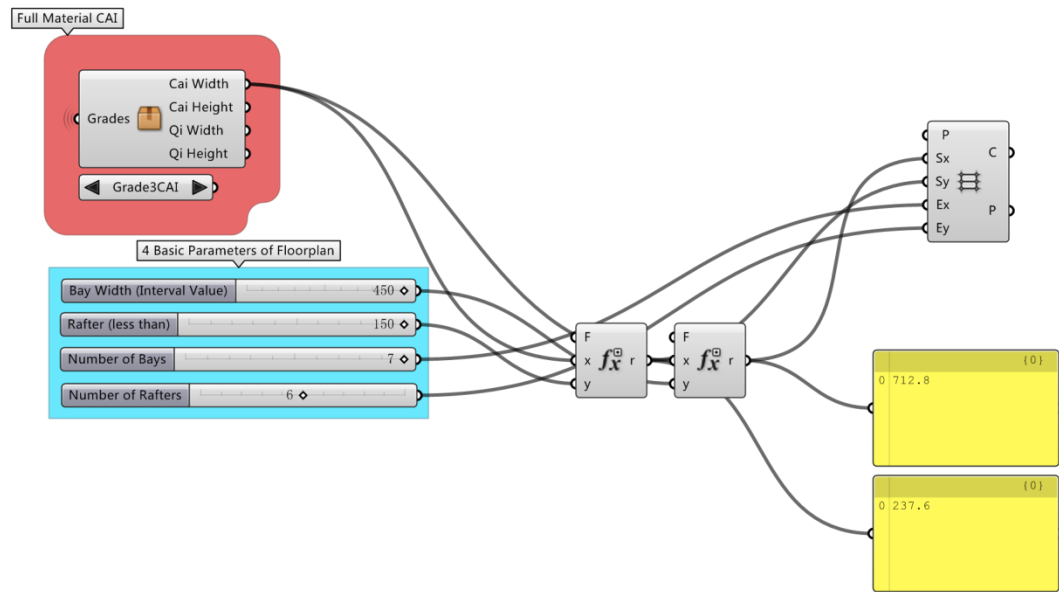
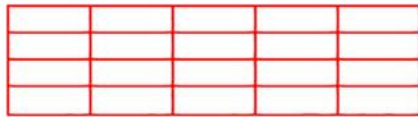
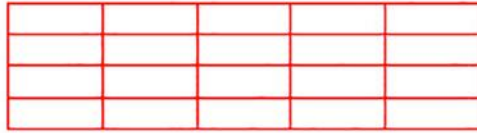


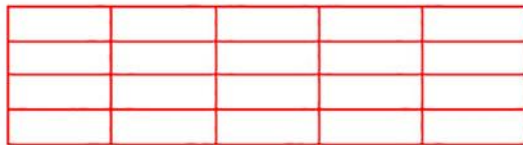
Figure 109. Attempt 2 modelling process



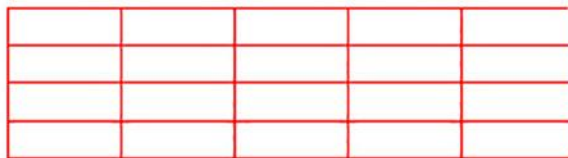
Grade 1



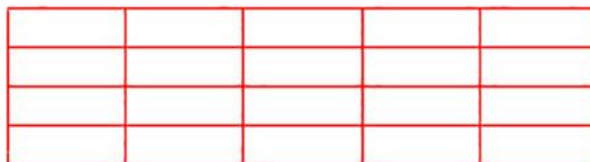
Grade 2



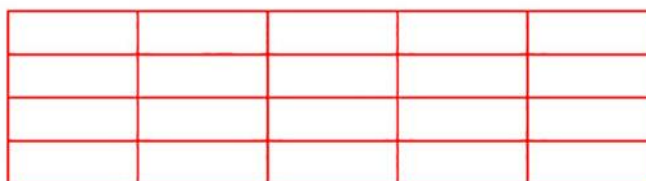
Grade 3



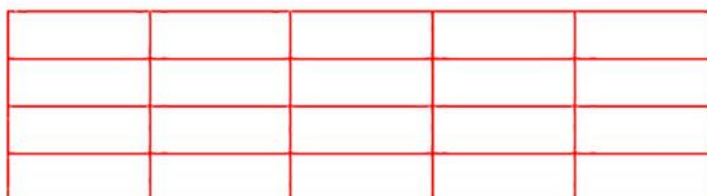
Grade 4



Grade 5



Grade 6



Grade 7

Figure 110. Grade 1—7, 5 bays, 4 rafters floor plan examples (variable: grade of *Cai*)

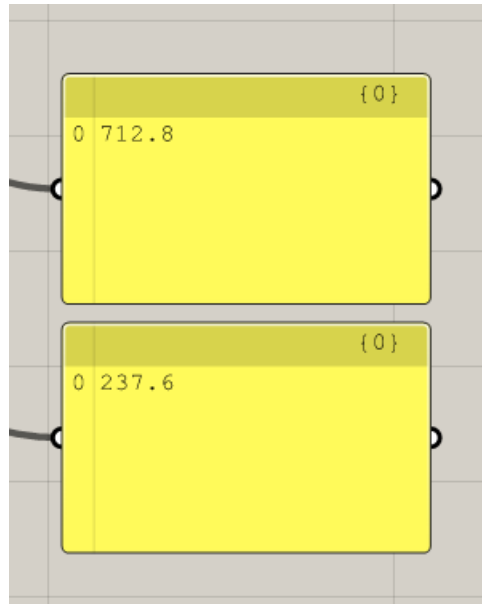


Figure 111. Outputs of attempt 2—building width and building depth

3.4.3 Attempt 3—column positions and podium

In this attempt, two supportive elements—column positions and podium will be included into the floor plan model. Figure 112 is shown as an example, Liang did his research in a very standard format such that producing the floor plan diagrams with the podium (the outer rectangle outside the floor plan grids) and other relevant information, especially, the column positions (the black dots). Although such information does not directly belong to the floor plan, they are relevant to complement the floor plan research. Therefore, in this research, to be consistent with Liang's format, column positions and podium will be modelled. Additionally, if the section case studying is taken into consideration, the column position will be a key factor in the algorithmic presentation of the section. It is the link between the floor plan and the section.

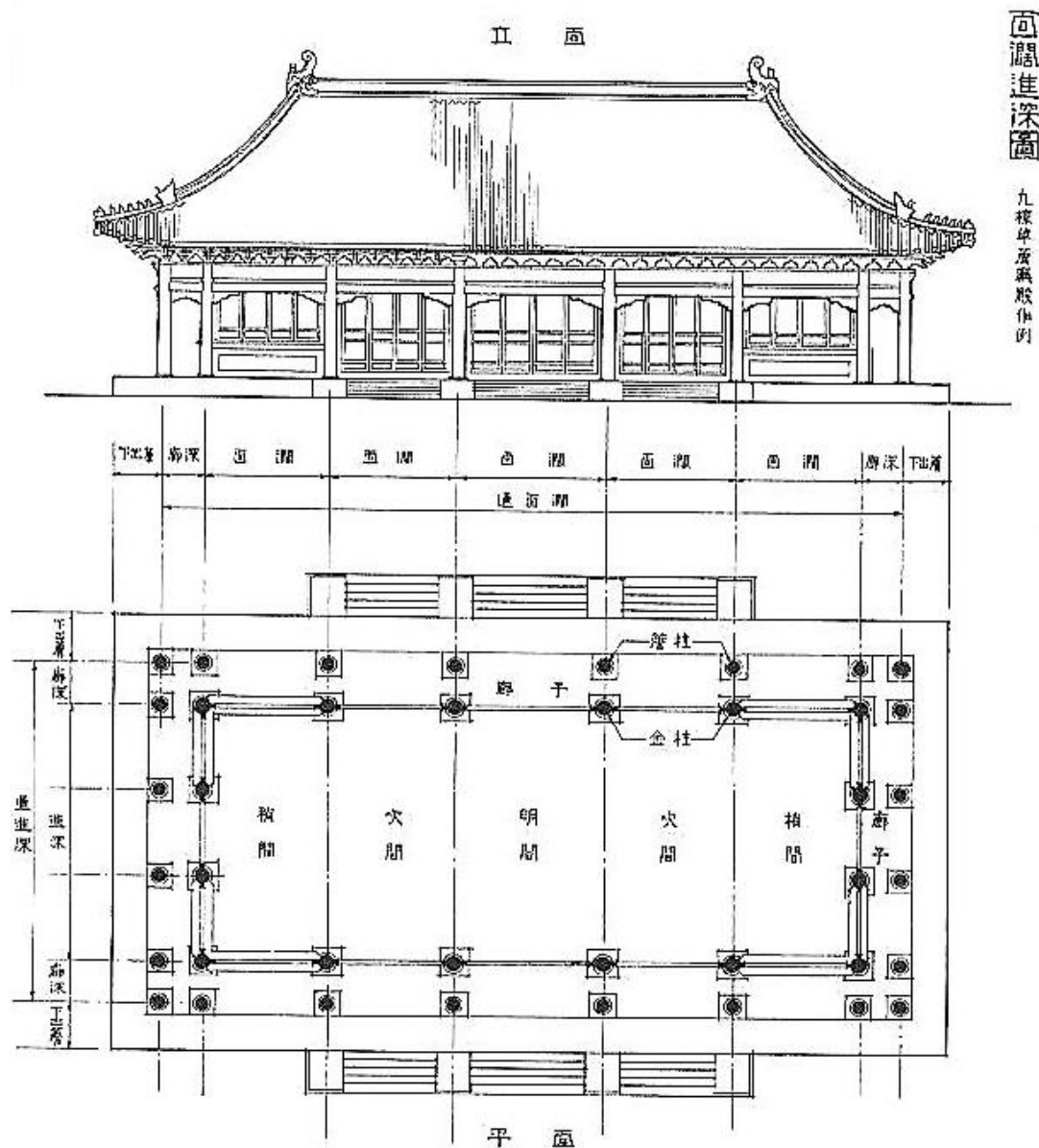


Figure 112. Liang's example of a floor plan diagram and relevant information from *Qing Shi Ying Zao Ze Li* (Liang, 2006, p. 91)

To get the column positions, there is no need to find out and define the positions manually. As introduced in section 3.2 and shown in Figure 86, in principle, the four corners of a bay (marked by black dots) should be the column positions. In practice, these positions may not necessarily be filled by columns, but they can be. Therefore, in modelling process, these positions can be obtained by exporting the bay-corners' set points. In this way, all the positions will be allocated, no matter that in reality they are required or not. If some are not required, the exporting can be turned off or partially turned off (this will be shown in the following attempts). Figure 113 shows

the method to export the positions in Grasshopper by a list after tidying up the algorithm of the floor plan. All the coordinates of the set points can be obtained from this list. Figure 114 shows examples of the floor plans of eight grades with column positions.

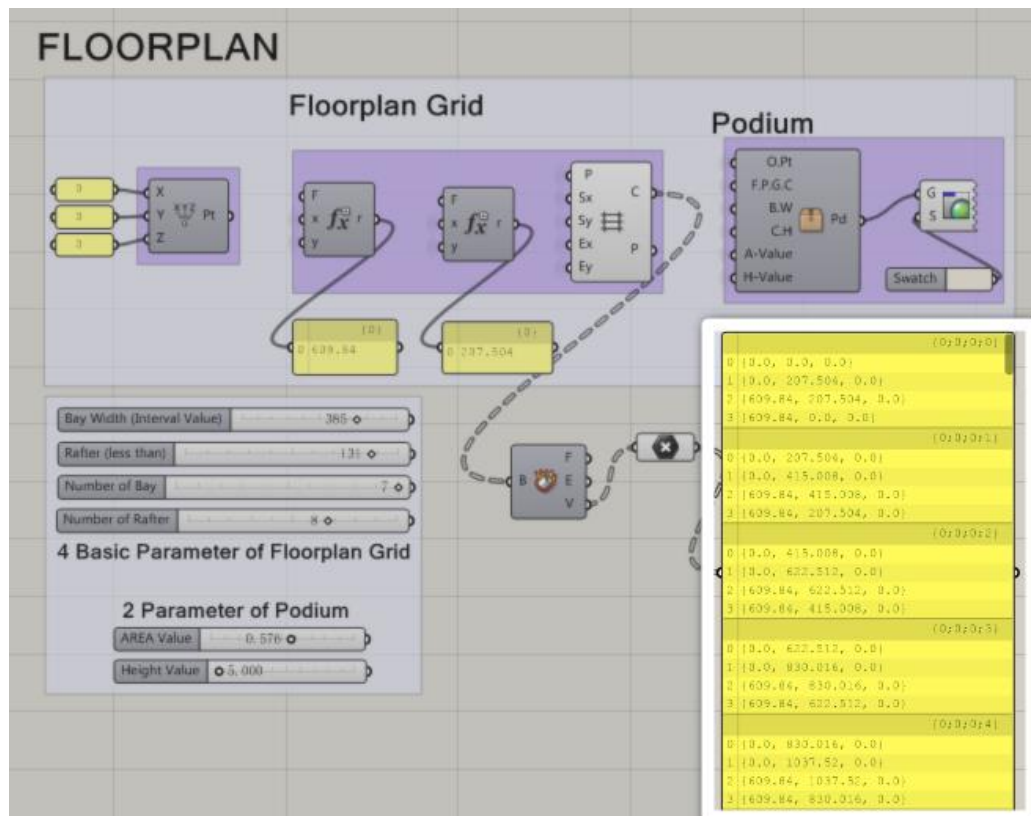


Figure 113. Export column positions in attempt 3

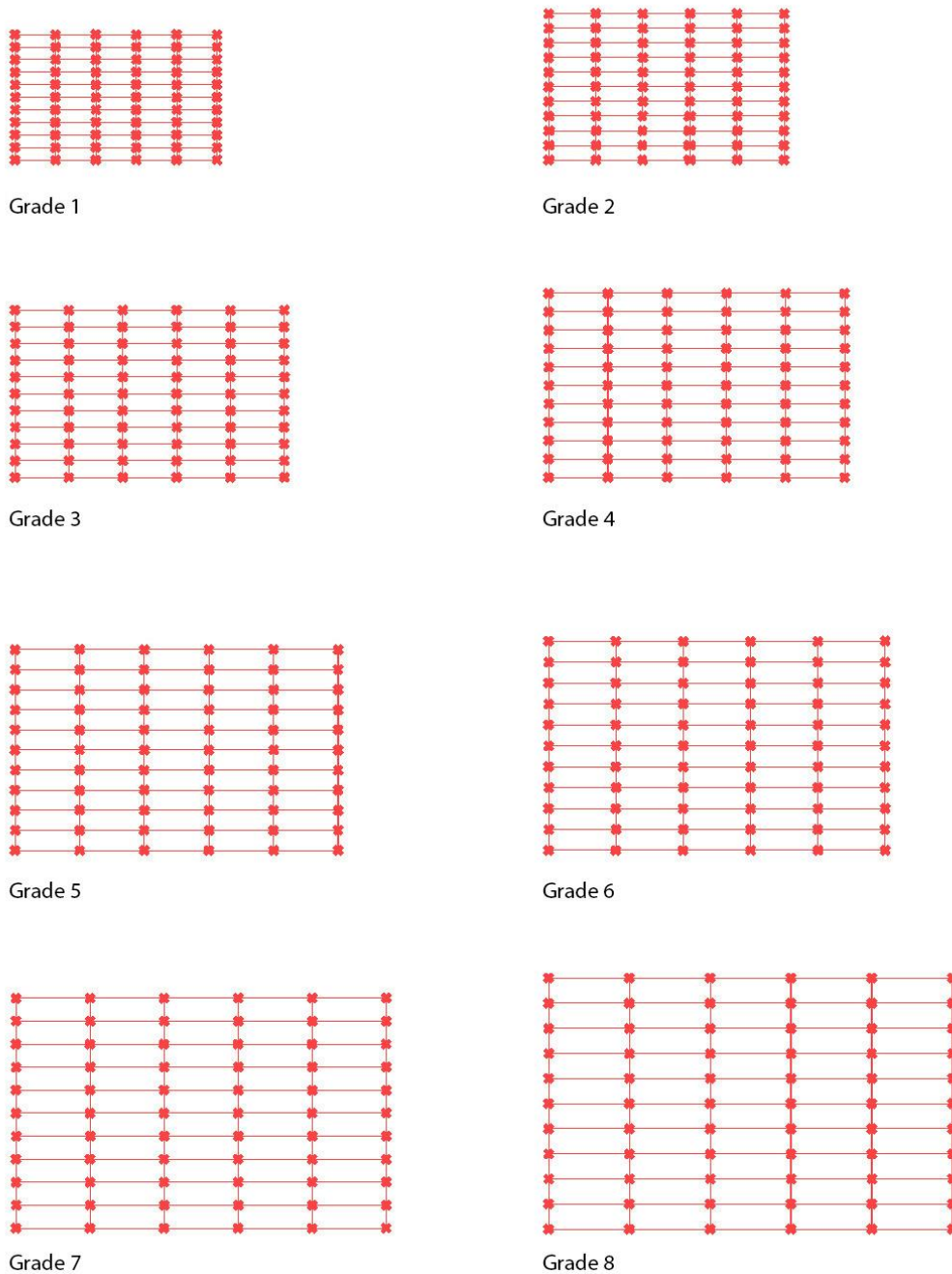


Figure 114. Examples of the floor plans (5 bays, 10 rafters) of eight grades with column positions

There are two factors to define the podium - podium area and podium height. The podium area consists of two parts: the floor plan grid area and the extra area. So far the floor plan grid area is known from the previous attempts, the only required data is the extra area. To obtain such data, it is required to know that the distance between the central points of eaves columns (outermost columns) and the edge of the podium. But based on Liang's research (Liang, 1983), "this distance is not defined in *Ying*

Zao Fa Shi". On the other hand, based on the analysis and statistics to the floor plan drawings included in the book *Ying Zao Fa Shi Zhu Shi* (The annotated *Ying Zao Fa Shi*), the range of this distance can be summarised as: it is less than the bay width, and between 0.389 to 0.722 times of the bay width, also varies depending on the building overall scale and level. Once this distance is obtained, the extra area can be calculated in the way of adding up all the four extra rectangles outside the floor plan grid. The podium height is summarised by Liang (Liang, 1983) that the height is five to six times as the *Cai* height. Thus, the formulas used in modelling are shown in Figure 115.

$$\text{distance} = 0.389 \sim 0.722 \text{ bay width}$$

$$\text{podium height} = 5 \sim 6 \text{ Cai height}$$

Figure 115. Formulas used to calculate the podium area and height

Figure 116 shows the two new parameters added into the algorithm to present the podium. They will be connected to the algorithmic functions of the podium modelling process (see Figure 117). Again, to keep it simple and clear, the podium algorithm is grouped as a cluster, as shown in Figure 118. Figure 119 and Figure 120 show the examples of different podium areas and heights respectively when changing the parameters' input. Figure 121 shows the overall modelling process of this attempt with column positions and podium. Figure 122 shows the examples of eight different grades floor plans with the information of column positions and podium. Other parameters of bays and rafters can be changed parametrically as well, the same as in the previous attempts. Here it is not going to show all of them again.

Bay Width (Interval Value) 385

Rafter (less than) 131

Number of Bays 7

Number of Rafters 8

4 Basic Parameters of Floorplan Grid

2 Parameters of Podium

AREA Value 0.576

Height Value 5.000

Figure 116. Two more parameters of podium in attempt 3

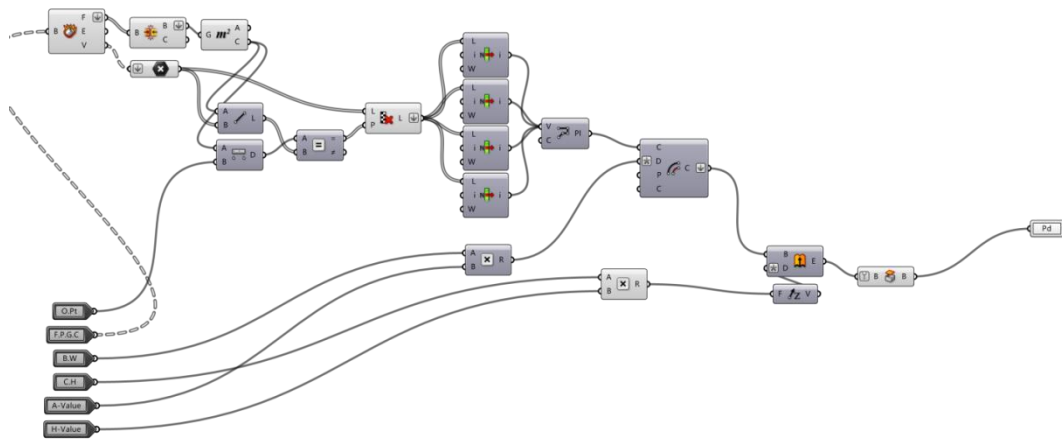


Figure 117. Podium modelling process in attempt 3

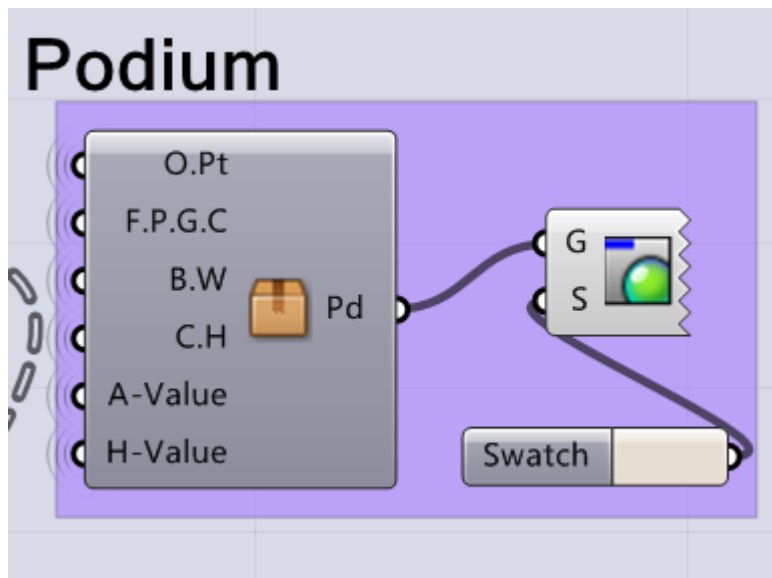


Figure 118. Podium cluster in attempt 3

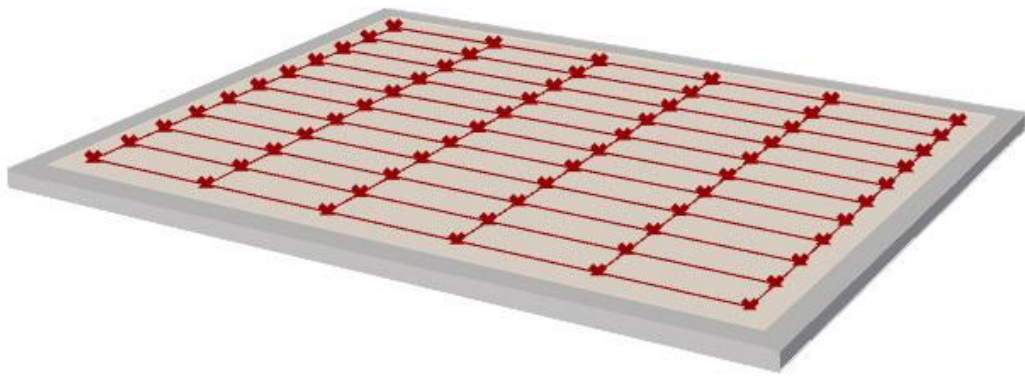


Figure 119. Examples of different podium areas

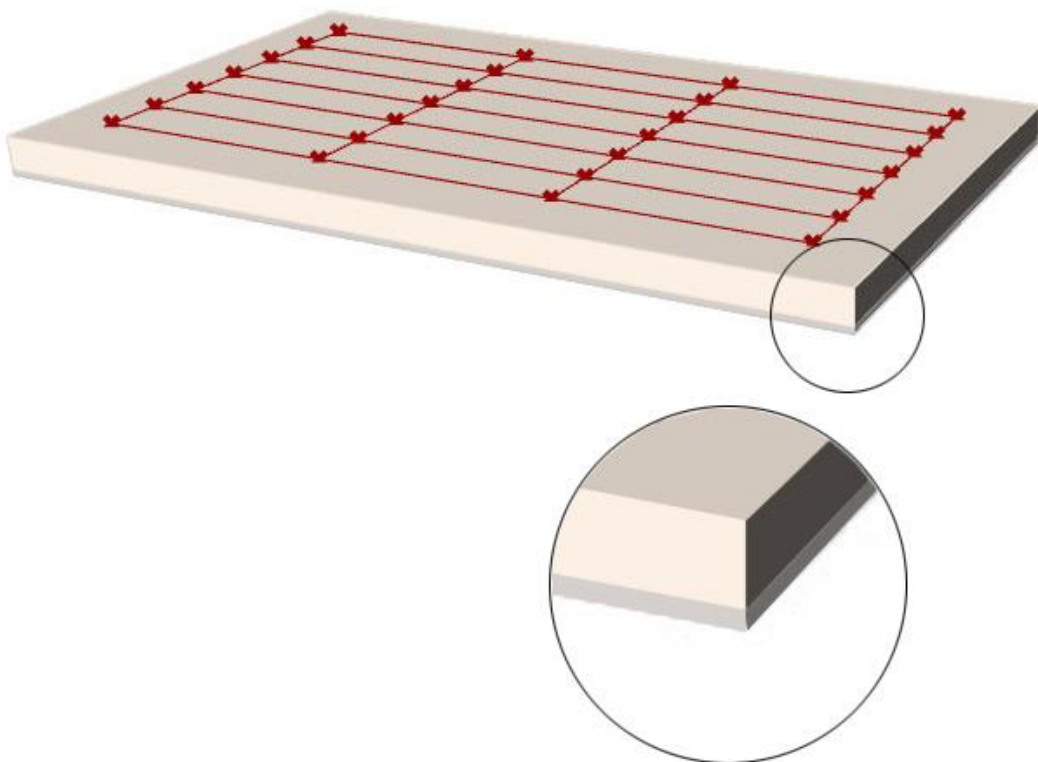


Figure 120. Examples of different podium heights

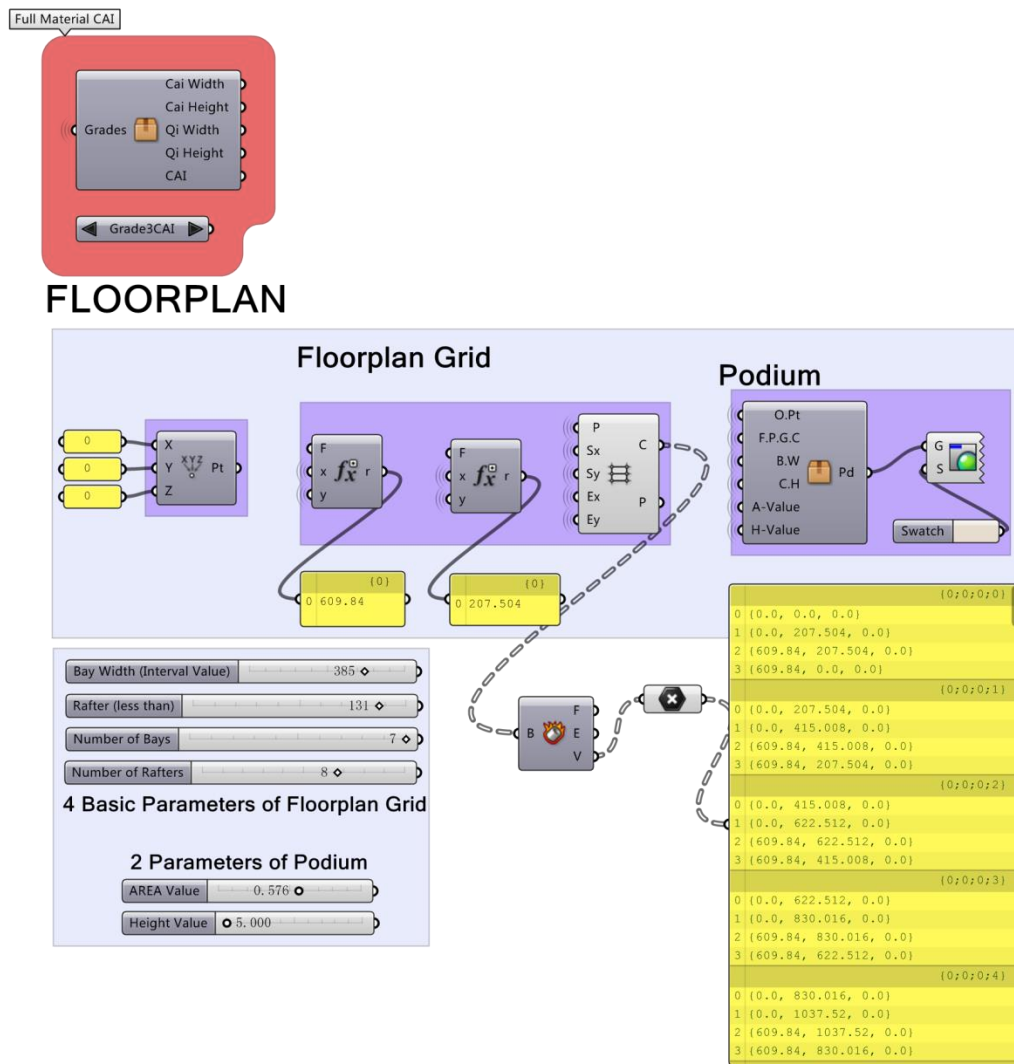


Figure 121. Overall modelling process of attempt 3 with column positions and podium

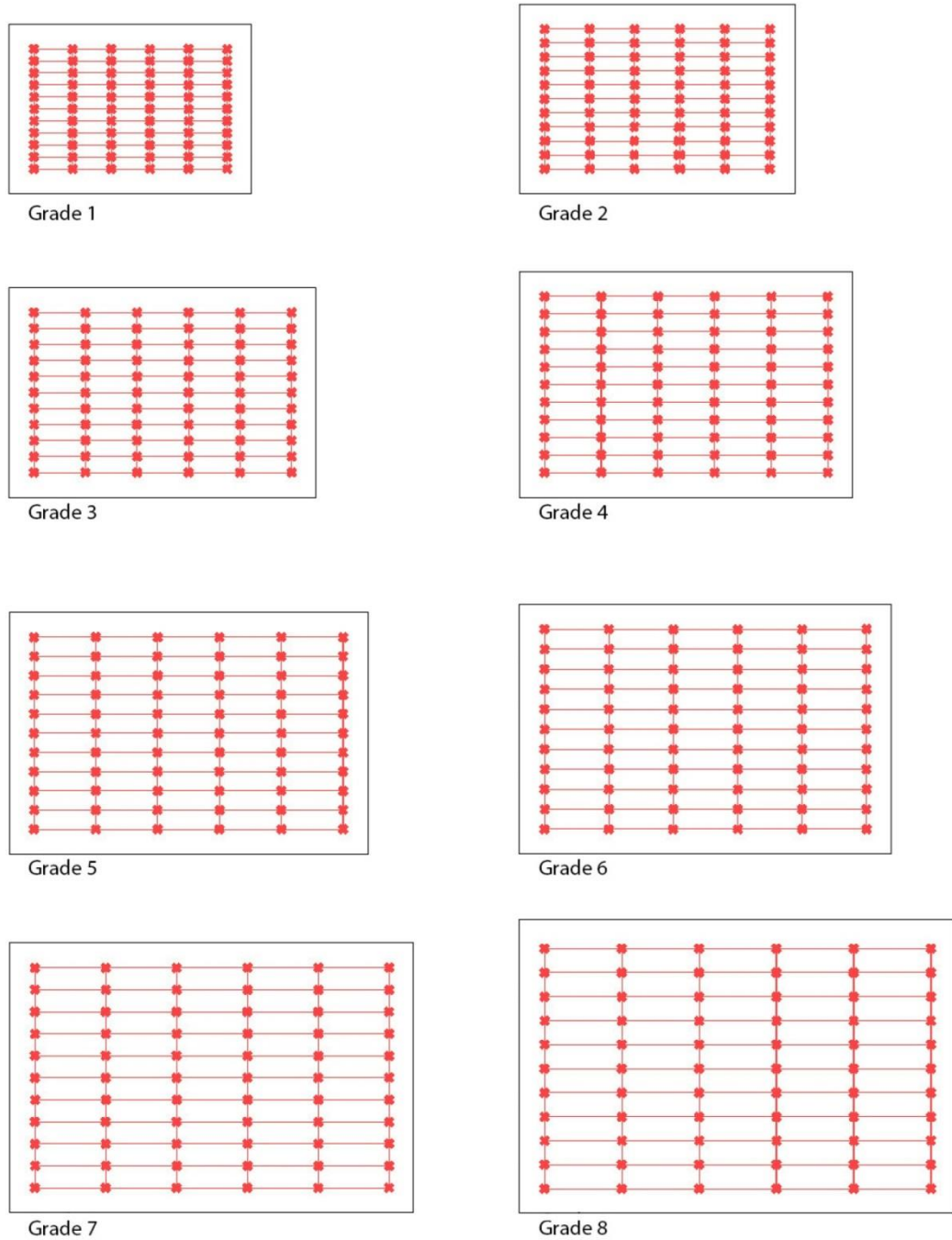


Figure 122. Examples (5 bays, 10 rafters) of eight grades floor plans with column positions and podium

3.4.4 Attempt 4—optimisation

As mentioned in the last section, the export of the columns can be turned off if not needed, as shown in Figure 123. Also in this attempt, the tests are extended to cover all the range of bay number and rafter number, which is, from one to eleven bays,

and from two to ten rafters. Although in the definition, the number of rafters could reach twelve, in reality, there is no twelve rafters extant building found so far. Thus, in this research, the upper boundary is set as ten. If in the future the information is updated, this parameter's boundary could be easily modified. And this does not affect the modelling process. Figure 124 and Figure 125 show 1—11 bays and 2—10 rafters floor plan examples respectively. Until now, all the variations of bays, *Cai*, podiums and control of column positions could be achieved in this optimised attempt.

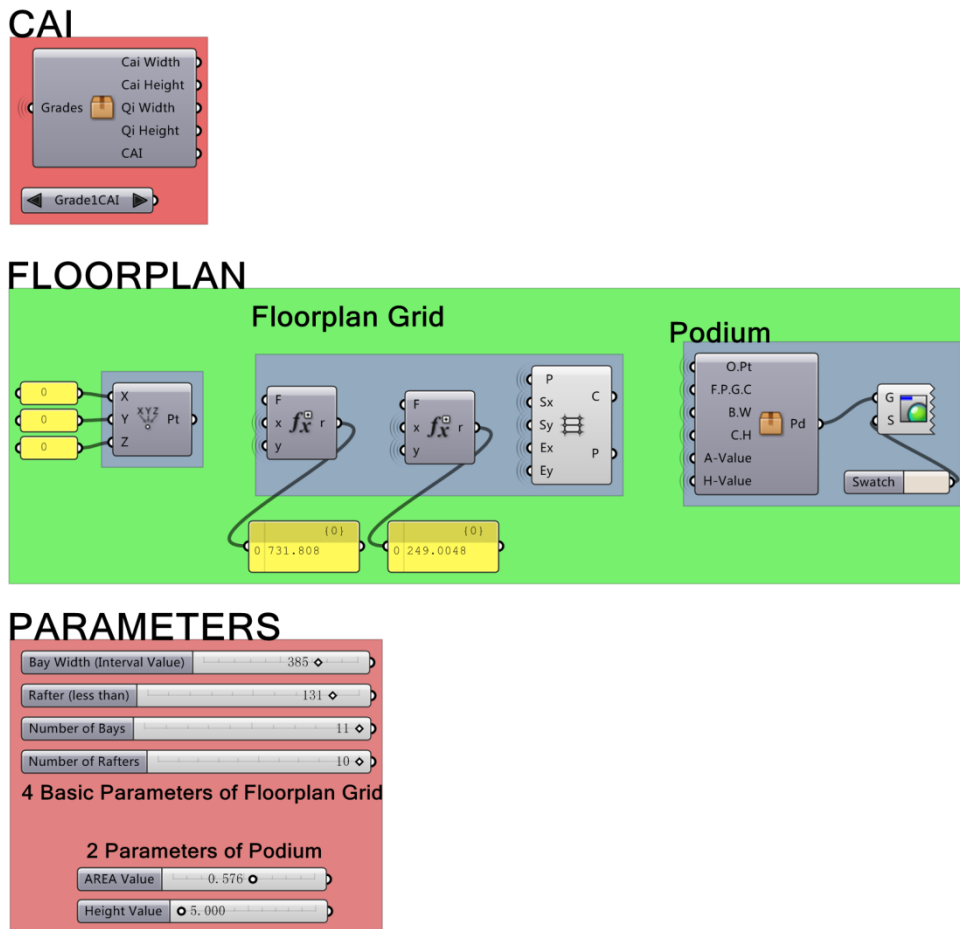


Figure 123. Optimisation in attempt 4

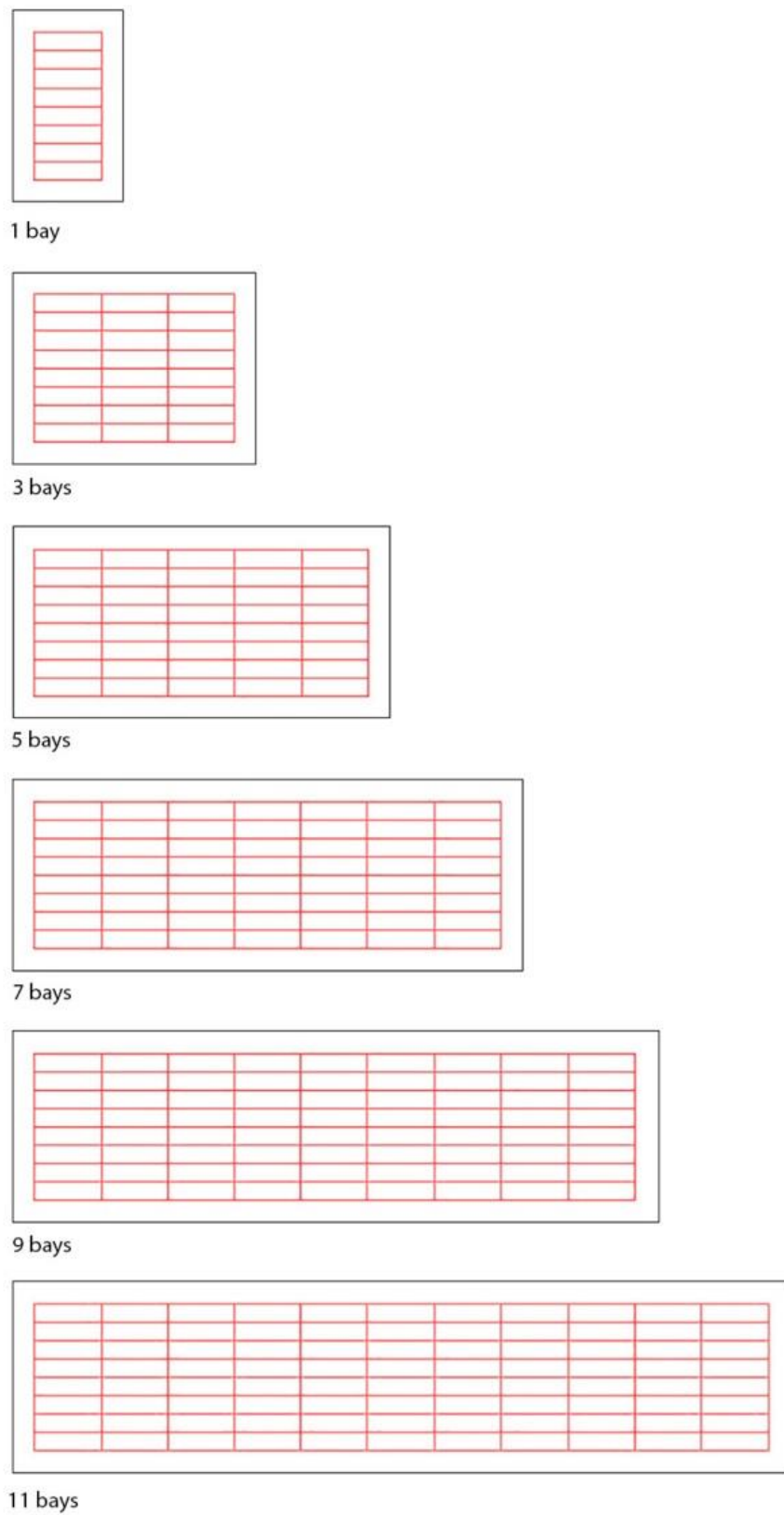


Figure 124. 1—11 bays, 8 rafters floor plan examples in attempt 4

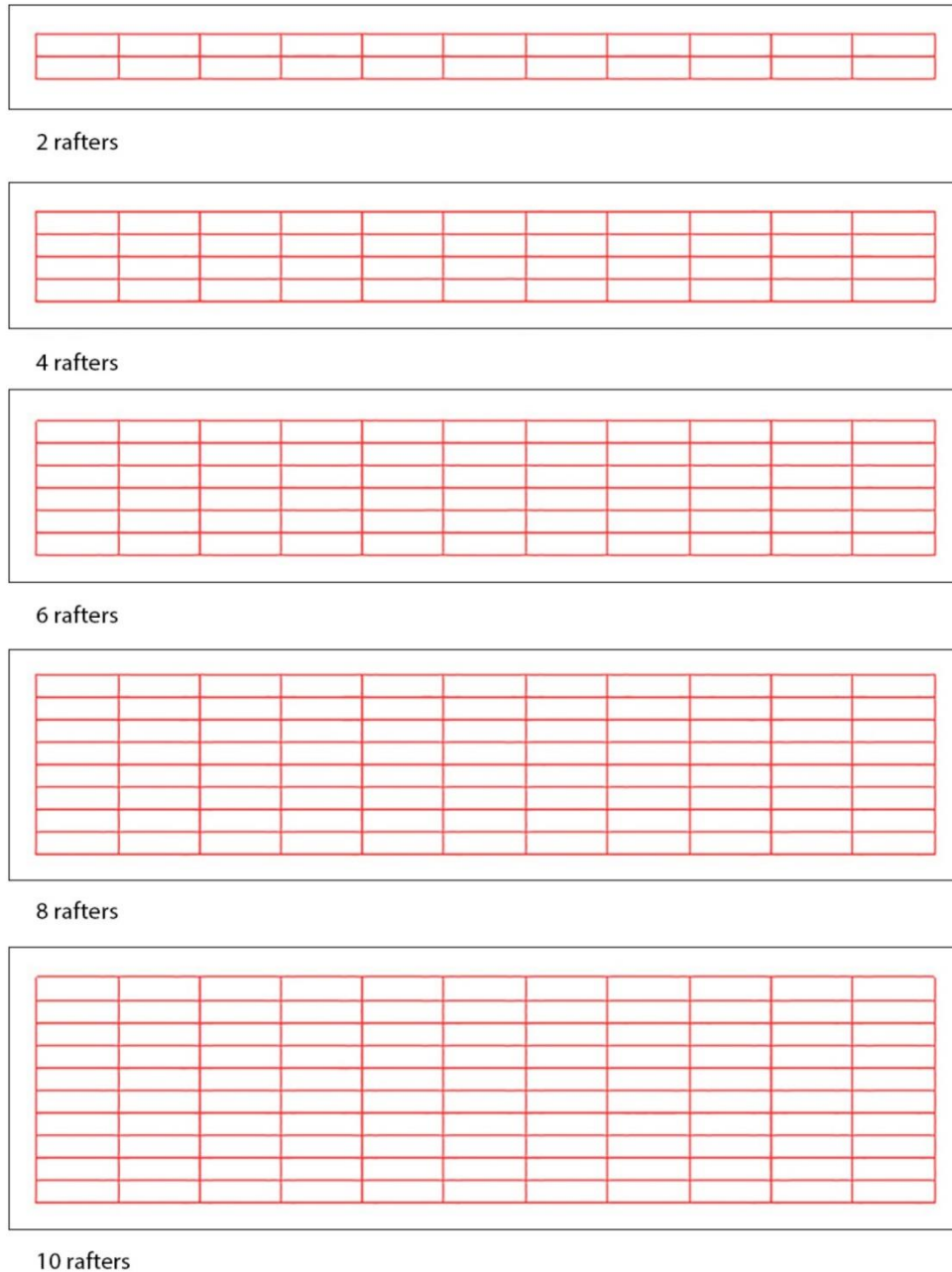


Figure 125. 11 bays, 2—10 rafters floor plan examples in attempt 4

3.4.5 Attempt 5—further optimisation

Although the floor plan parametric modelling was successful in the last attempt, in order to better link with the section case study, a further optimisation will be tried. First, considering the section modelling process will be more complicated, a further simplification of the floor plan algorithm is required. So the floor plan grid part (see Figure 126) is grouped as a new cluster as shown in Figure 127. And so far all the

individual components are grouped together respectively as clusters in the main control panel.

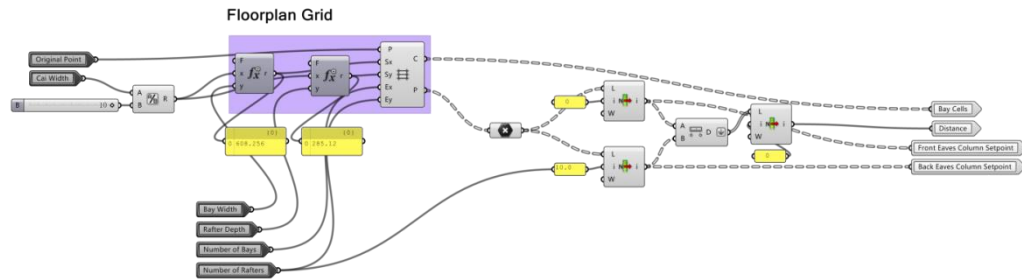


Figure 126. The floor plan grid part in attempt 5

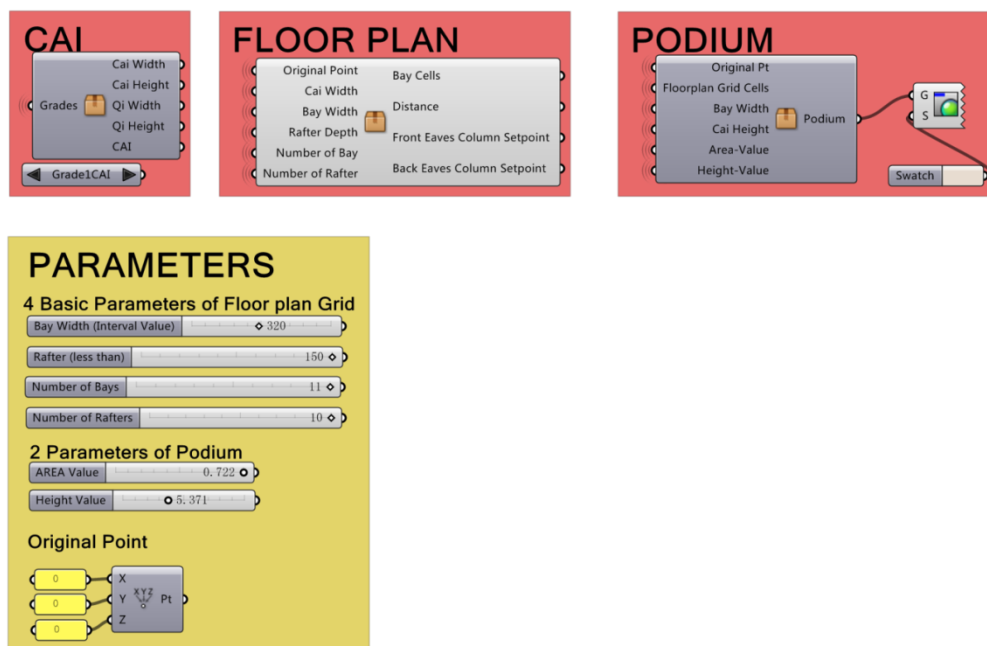


Figure 127. All components are grouped as clusters in attempt 5

Apart from this, in one of the attempts in the section case study, the front and back eaves column positions are required. Also, as mentioned in the previous attempt, the export of the column positions can also be partially turned off (which also means partially turned on) according to the need. In other words, the column positions can be shown or not shown based on the requirement. As shown in Figure 128, this can

be achieved by optimising the algorithm of the floor plan grid part. And the corresponding example is shown in Figure 129, which only shown the front and back eaves column positions.

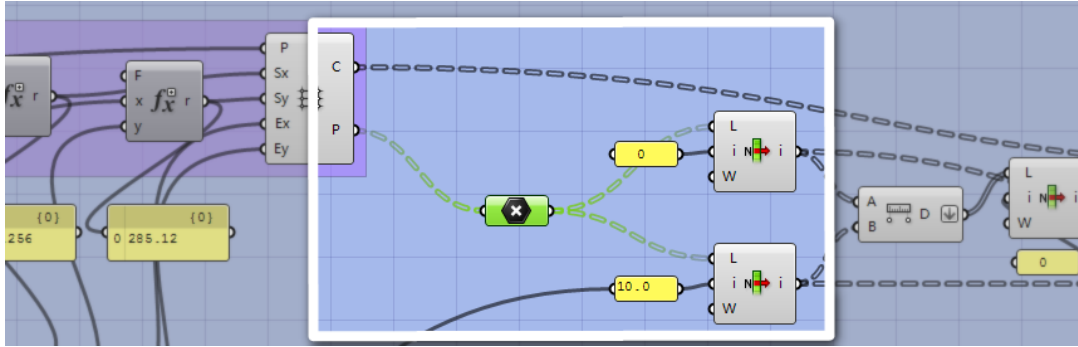


Figure 128. Control of the export of column positions

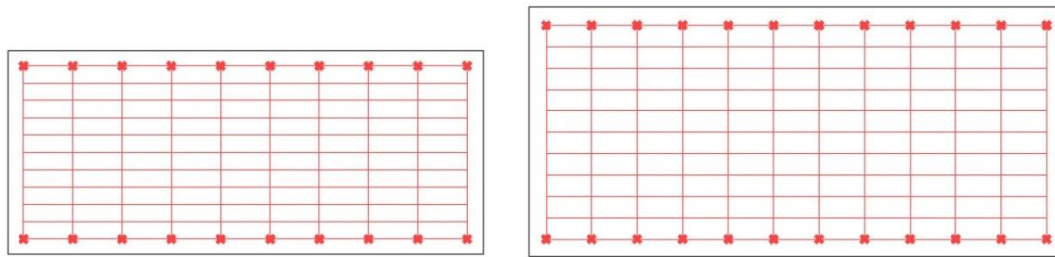


Figure 129. Examples of showing only front and back eaves column positions

3.5 Comparison with extant building data

Comparing the examples with the diagrams in *Ying Zao Fa Shi* (Figure 60 right), they are highly consistent in form, including the grid system and column positions. But since the diagrams in *Ying Zao Fa Shi* are only abstract demonstrations, as well as they do not contain accurate information nor present any specific buildings, they are not the standard to judge the parametric models.

Consequently, the comparison with extant building data is a reasonable verification at this stage. Set one extant building—Fuoguang Temple Wenshu Hall (see Figure 130) as an example. It was built in 1137 at the Jin Dynasty (which was parallel as the Song Dynasty in northern China), located at Shanxi province Mount Wutai. According to Liu (Liu, 1984, p. 246) and Wang (Wang, et al., 2011, p. 73), it is believed to be a Grade Two *dian tang* type building with seven bays and eight rafters. Although some may argue this building should be *ting tang* type and the level is in

between Grade Two and Three, and is closer to Grade Three (Mimike, 2013), the debatable information has no impact since the parametric modelling process includes all these types and levels. From the parametric model, the minimum building width for Grade Two and seven bays building is given as $7 \times 200 \times 0.55 \times 32 = 24640 \text{ mm} = 24.64 \text{ m}$ while the maximum is $7 \times 450 \times 0.55 \times 32 = 55440 \text{ mm} = 55.44 \text{ m}$. Similarly, the building depth spans from 15.84m to 21.12m. Wang (Wang, et al., 2011, p. 69) provides the measurement data of this building as 31.56m in width and 17.60m in depth. The measurement data is within the output boundary of the parametric model numerically, which means, one of the parametric models could present this building. In addition, as Liu (Liu, 1984, p. 246) points out that “there is not such an extant building completed follows *Ying Zao Fa Shi* found so far”, if the measurement data is within the range of the parametric model, then the two are consistent. Furthermore, if a comparison is made between the site drawing (see Figure 131) and parametric model floor plan (see Figure 132), it is obvious that the two are extremely consistent geometrically. All the aspects including grid system (bays), information of *Cai*, column positions, podium, building width and building depth can be presented. Meanwhile, the parameters used to generate this building are also clearly shown in Figure 132.



Figure 130. Fuoguang Temple Wenshu Hall (Anon., 2015)

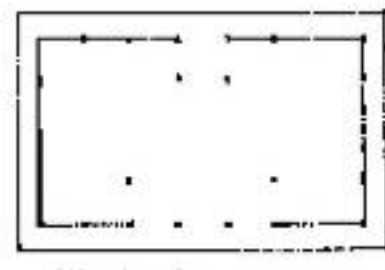


Figure 131. Fuoguang Temple Wenshu Hall site drawing (Wang, et al., 2011, p. 55)

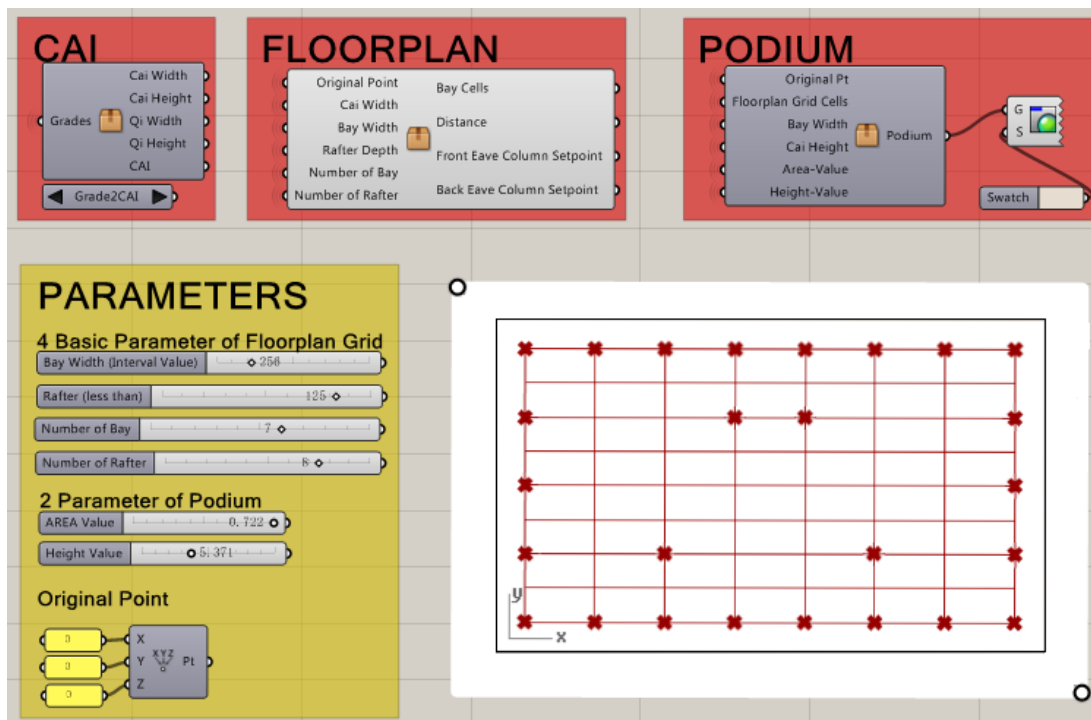


Figure 132. Parametric floor plan of Fuoguang Temple Wenshu Hall

The above comparison is one of the successful examples and verifications could also be made on the rest of extant ancient buildings. Another eighteen historical sites have also checked with similar and consistent results also being found.. Considering there are not many extant ancient buildings found in China so far, the parametric models can definitely present much more than those buildings, such as the lost, damaged or unbuilt ones. Therefore the parametric models can present the traditional Chinese style following *Ying Zao Fa Shi*.

3.6 Discussion, conclusion and future work

Parametric design differs from the conventional design mode of adding and removing marks in that the relationships between the parameters are the essence of parametrics. In this case study, the relationships are not based on one specific example to only model one building, which the majority of parametric attempts on Chinese architecture do in recent studies, such as those included in Bao's work (Bao, 2013). But in this case study, the relationships are from a systematic description and summary of a building style in a typical period—which are the rules. The basic algorithm of the formal rectangular floor plan is then built up based on the rules. Following this, different outcomes can be generated to indicate the advantages of

parametric method which can result in different final products without a new set of algorithm or the removal/addition of individual components. And in this process optimisations are made to include more information and better control the end products. By the end, all the floor plan formats containing the major indicated information are included in this set of algorithm, including the two building types (*dian tang* and *ting tang*), any dimensions, all the grades, column positions and podium. During the whole process, several points could be discussed as follows.

First, although the algorithms are mainly based on the rules following *Ying Zao Fa Shi*, by adding in the relationship between Song style and Qing style (which has been briefly discussed in earlier chapters), it is possible to include Qing style into this set of algorithm in the future to complete the database of traditional Chinese style. And similarly, if more information (such as texture, detailed finishing or material property) needs to be included at a later stage, they can be added in and linked together. In other words, based on this case study, more options and details could be obtained continuously making it useful in design.

Second, apart from including more information, if any of the current information in use is updated or proved to be inaccurate, modifications can be easily made and there is no impact on the overall algorithm. For example, if the absolute value 1 *cun* = 32mm is updated to a new value, the export of building width and depth will be automatically updated. And if a twelve rafters building is found later, the boundary of rafters could be raised up to 12 instead of 10 and then immediately include more outcomes.

Third, there are two outcomes of the parametric process: numerical data (such as the building width and depth) and geometrical model. They are convenient in comparing information and generating new designs so both useful in further research and design.

Forth, if verification is required, there are three general methods. Since the modelling process is rule based, to check with the parameters selection, their boundaries, the relationship between different factors and the logic in algorithm is the fundamental method. Apart from this, the output data could be used as a quick and rough check compared with the known data in order to understand a reasonable range. Additionally, this can also be achieved by comparing with the real site drawings on the geometry and details.

Fifth, as mentioned above, there are limited extant ancient buildings but the parametric modelling can present much more than those. This makes it possible to further investigate and interpret the Chinese style by reproducing lost or damaged buildings, as well as simulate unbuilt buildings.

Sixth, from this case study, it is proved that merging together the *ting tang* and *dian tang* types of buildings in the representation of the floor plan is acceptable and efficient. But whether the two types can be merged together in modelling process in other case studies would require further investigation.

Seventh, in this case study, considerations are also given to the factors related to the section case study, such as the use of rafter and the export of column positions, making it a good preparation for the next case study. Apart from these obvious linkage, a deep and essential relationship that links the floor plan and the section, and even all the rest parts, is the utilisation of the concept of *Cai*. Under this concept, all the parameters and boundaries of the parameters are defined and described by *Cai*, and all the logics between parameters are built up based on *Cai*. This is why at the beginning of the carpentry volume of *Ying Zao Fa Shi*, Jie Li specifies “凡构屋之制皆以材为祖 (in all types of constructional rules, *Cai* is always the fundamental concept)”. In particular, the use of modular units and the distinction of the material levels are the important aspects in this concept.

Overall, some conclusion can be drawn as follows. First, all the major factors and relationships define the rectangular floor plan are included in the modelling process with a certain flexibility to update if required. With the initial requirement (input), based on the algorithm (rules), different floor plan variations and relevant data (output) can be obtained. Second, parametric method shows advantages in the floor plan case study considering the floor plan system has specific regulations, and meanwhile includes a large number of variations. Third, the modelling process is a gradually optimised process consists of several attempts step by step and with different focus. In the later case studies, when the algorithm becomes much more complicated, this feature will be more obvious. Otherwise an overloaded blueprint at the beginning will lead to a failure. Forth, the modelling process is based on the concept of *Cai*, and this concept is the most important essence to relate all the case studies together. Fifth, the aim of this case study (and also for the entire research) is to build up the modelling process that presents a certain style rather than a typical building's model. And also, to identify the advantages and disadvantages of the parametrics during this process.

In this case study, some aspects are omitted and can be included as future work. First, in the floor plan grid system, there is a phenomenon that the middle bay(s) might be slightly wider than the edge bays (Wang, et al., 2011, p. 61). The influence of this bay width change is fairly minor thus not considered in this case study. And due to the lack of solid descriptive rules on this and the lack of statistics from the extant building data, how to set the range of this variable requires further study. Second, the export of column positions in this case study is mainly based on the most common compositions, which are, the entire row(s) or the entire line(s). There is a lack of descriptive rules or statistics from the extant building data that how the inner columns (the columns inside the grid area) vary. Once this can be understood, a more intelligent selection of the exported column positions can be proposed. Third, the method of “reducing the number of the columns” (introduced in section 1.1.1.1 and Figure 18) and “changing the position of the columns” might be started since the Song dynasty (Liu, 1984, p. 246). This also influences the export of the column positions. But again, there is a lack of information on the rules of how to reduce or

change the columns. Thus, the most regular column setting (with the entire row(s) or line(s) filled by columns) remains in this case study unless there is a specific extant example. Forth, the Qing style can be included based on the definition of “the rule of material in Qing Dynasty” (introduced in section 1.1.1.1) and the module difference introduced in Figure 63.

Chapter 4 Case study 2—section

Following the last case study of the floor plan, this chapter concentrates on the section case study, which is another key aspect reflecting the traditional Chinese style. Similarly, *Ying Zao Fa Shi* provides the basic rules and instructions in the interpretation. Meanwhile, since there are important information omitted from *Ying Zao Fa Shi*, relevant previous research and hypotheses are taken into consideration in assisting the modelling process using Grasshopper and Rhino. In the modelling process, there are a series of frustrations compared with the floor plan case study, due to the complexity and variation of the section. Three major attempts are carried out based on three different concepts. In particular, the later ones are not the optimization of the former ones. They are new strategies based on the analysis of the former failures and the summary of the former success. The discussion and evaluation are made by the end. Future works are suggested as well.

In order to understand the rules and derive the algorithm for parametric process, the same as last case study, the rulebook *Ying Zao Fa Shi* (and therefore, the Song Style) is the primary basis. Qing Style (with the reference of *Gongcheng Zuofa Zeli* and *Qing Shi Ying Zao Ze Li*) is the important reference, and it has the certain relationship with the Song Style. Liang's wide range of research and analysis on the two rulebooks and field trip information are reviewed as a constructive reference and a compliment to those omitted information in the rulebooks. Also, Pan's studies and analyses (Pan, 2009) are reported in a number of texts and both comprehensive compendium on history of Chinese architecture and details describing the building types and components are useful resource. Li's Shape Grammar research focused on the *ting tang* section (Li, 2003) is more recent and applies the CAAD based environment to this topic. Therefore it is used as a key comparator to start this case study. Apart from all these, since the information for parametrics is not sufficient, hypotheses based on the author's derivation are made in the modelling process.

There are two significant reasons of selecting the section as the second case study in this research. First, the section has close relationship with both the floor plan and the *dou gong*. Based on the concept of *Cai*, the algorithm of the section is consistent with the other two case studies. Second, upon the completion of the section modelling, the study of traditional Chinese style is from two dimensional to three dimensional (this will be further discussed in Chapter 6). In other words, with the integration of the floor plan and the section, the major timber frame structure is built up. Although there are separate studies on the elevation from a conventional point of view, the intelligently generated major structure is practical in design. This in turn provides an option in practice to revive the Chinese style that respects the history and culture.

4.1 Description of the ancient style section

There are three main structural types of traditional timber frame Chinese architecture, as shown in Figure 133. The first one is *Tai Liang Type*, means post-and-lintel construction, in which horizontal beams are on top of vertical columns and meanwhile hold upper beams by wood cushion or short columns. The upper beams are in the bay depth direction and they become shorter layer by layer from bottom to top. On the very top layer, there is a short column or a small triangular brace at the middle of the beam, making the roof area of the section a triangle shape. *Ying Zao Fa Shi* mainly concentrates on this type in its carpentry volumes. The second is *Chuan Dou Type*, means column and tie construction, which does not use beams. In the bay depth direction, there is a series of columns with one purlin (a vertical short column-like wood) on each column. The load is passed to columns through the purlins directly. Between columns, there are horizontal connections (called *chuan fang*) penetrate through the columns and tie them together. This type is more often in south China. In reality, a mixture of these two types sometimes appears in real examples (Pan, 2009, p. 91), so there might be an ambitious boundary for the two types in practice. The last one is *Jing Gan Type*, means log cabin construction, which uses wood sticks to stack and form the walls without the main columns and beams. This type limits the building size, as well as the door and window location, therefore is less commonly used compared with the other two types.

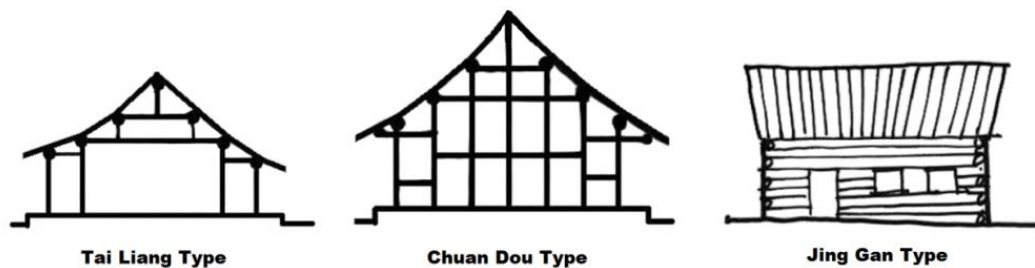


Figure 133. Three main structural types of traditional Chinese architecture

Tai Liang Type is the commonly used one, which appeared since the Chunqiu period (770BC—476/453BC, the Eastern Zhou Dynasty is further divided into Chunqiu period and Zhanguo period) or even early, and maturely developed in the Tang Dynasty. This is one of the reasons why in *Ying Zao Fa Shi*, *Tai Liang Type* is the focus in the carpentry volumes. Different from the structural types, Jie Li defines that there are three main building types: *ting tang*, *dian tang* and *yu wu*, which the first two are the most important and commonly seen types. For *ting tang* type (*ting* could mean living area in Chinese, see Figure 136), the inner columns and outer columns are not the same height, and the inner columns are higher than the outer ones. The *dou gong* is not necessary, as it does not have the structural function in this type. In

Tang and Song dynasties, *ting tang* is mainly used for lower level and smaller scale buildings. For *dian tang* type (*dian* has the meaning of palace in Chinese, see Figure 135), all the columns are the same height, and columns and upper parts of the building are connected by *dou gong* layer, which has the structural function. In Tang and Song dynasties, it is mainly used for higher level, important and bigger scale buildings. After Song dynasty, as the structural function of *dou gong* becomes less important due to the technology development, *dian tang* type is gradually disappearing and replaced by *ting tang* type from the structure aspect. Until Ming and Qing dynasties, *ting tang* type becomes the main building type from the structure aspect. On the other hand, the name “*ting tang*” and “*dian tang*” continued to be used in all dynasties, mainly indicating the scale, level and importance of a building, rather than their original definitions regarding the structure aspect. In addition, although structurally speaking *dian tang* gradually disappeared due to the loss of the structural function of *dou gong*, this type did not really disappear. In other words, in Ming and Qing dynasties, *dian tang* indicated those big scale, high level and important buildings with *dou gong* as decorations but without structural function. Therefore, strictly speaking, these “*dian tang* type” buildings are “*ting tang* type but look like *dian tang*”. Another interesting point is, although *Ying Zao Fa Shi* distinguished these two types clearly, in reality workers dealt with this aspect with the maximum flexibility, by mixing the two types together. Until now there is not any extant building found that strictly follows *Ying Zao Fa Shi* for the building type (Liu, 1984, p. 246).

In the book *Qing Shi Ying Zao Ze Li* (Liang, 2006), the similar drawings and section structures as described in *Ying Zao Fa Shi* can be found (see Figure 134), indicates the continuity of development of the section diagram from the Song style to the Qing style. Therefore, although the models attempted in this chapter are mainly based on *Ying Zao Fa Shi*, they share similarities with the buildings in other dynasties and generic in design concept.

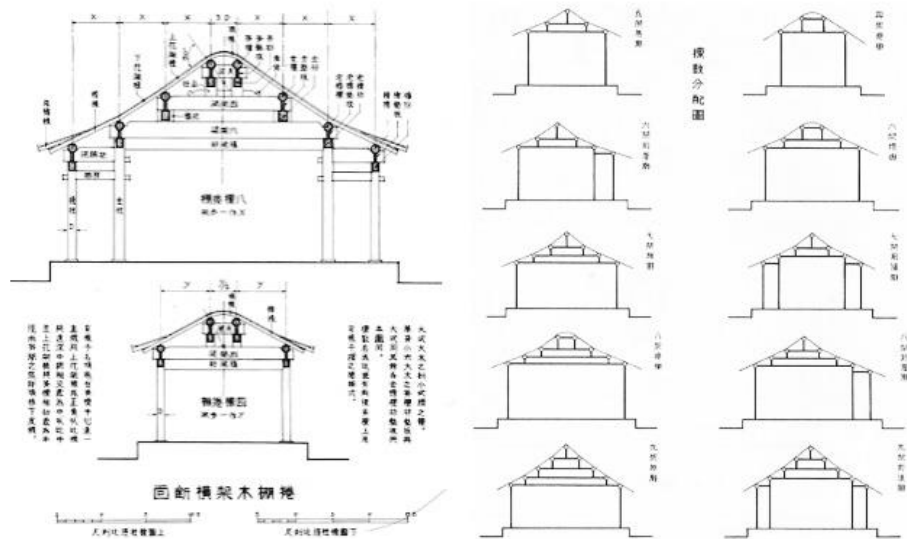


Figure 134. Section diagrams in *Qing Shi Ying Zao Ze Li* diagram 11 and 12 (Liang, 2006)

4.2 Parametric attempt 1—example based models with column focus

As introduced above, the section is more complicated than the floor plan and has ambiguity and overlap of the two major building types. Therefore these lead to the difficulty in the algorithm at the starting point. Unlike in the floor plan case study deriving the algorithm from the beginning, based on the literature review of Andrew Li's research, the example based, narrow and focused target—*ting tang* section could be the selected target in the first attempt. Meanwhile, the same target makes it a reasonable comparison with Li's study of shape grammar approach (Li, 2003) to this topic.

The aims of this attempt include the parametric models of the *ting tang* section using Grasshopper and Rhino, as well as an initial summary of this attempt. This is the basis for the later optimizations. Upon the achievement of parametric models of the selected examples, a more general and wide parametric algorithm can be gradually summarized. In this process, the potential variants that arise from a parametricisation of the rules and a consequent evaluation are discussed as well.

4.2.1 The understanding of *ting tang* section

This attempt is focused on *ting tang* type section based on the following considerations. First, since this type exists through all the ancient dynasties and relates with the other type, the investigation to *ting tang* type is also important for the understanding of *dian tang* type in later attempts. Second, *ting tang* section is

relatively smaller in scale, so it is appropriate as a starting point. Third, due to the extreme complexity of *dou gong*, the features of *ting tang* type is properly suited without the consideration of *dou gong*. And *dou gong* will be individually studied in Chapter 5.

In *Ying Zao Fa Shi*, unlike the floor plan, a number of the section diagrams are given in volume thirty-one, both *dian tang* (example shown in Figure 135) and *ting tang* (example shown in Figure 136) types. There are useful resources for example based modelling attempts. In a contemporary context *ting* means living area, and *tang* means hall. *Ting* tends to refer to lower level, smaller scale types of buildings in *Ying Zao Fa Shi*, while more formal buildings (such as temples or palaces) would be referred to as *dian tang*.

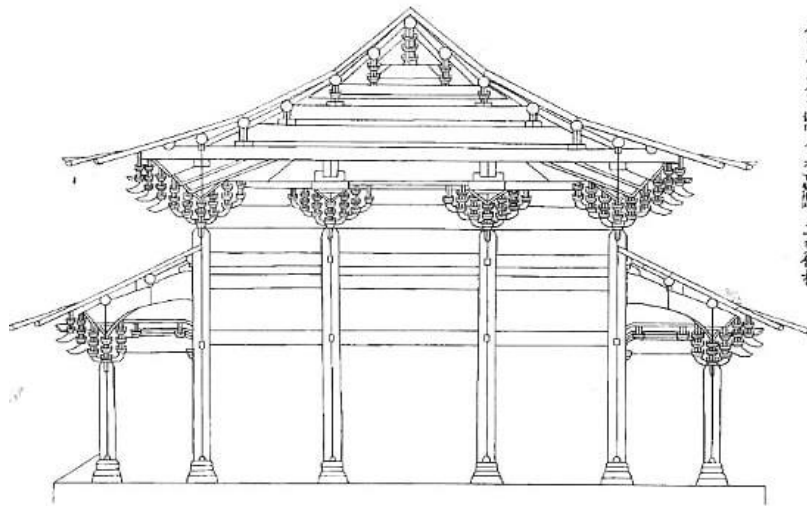
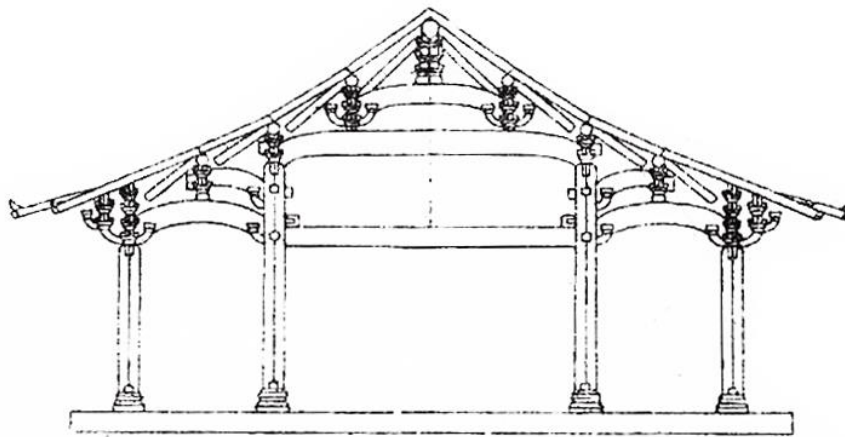


Figure 135. A *dian tang* example in *Ying Zao Fa Shi* (Li, 2006, pp. 756-757)



八
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梁
柱
間
距

Figure 136. A *ting tang* example in *Ying Zao Fa Shi* (Li, 2006, pp. 778-779)

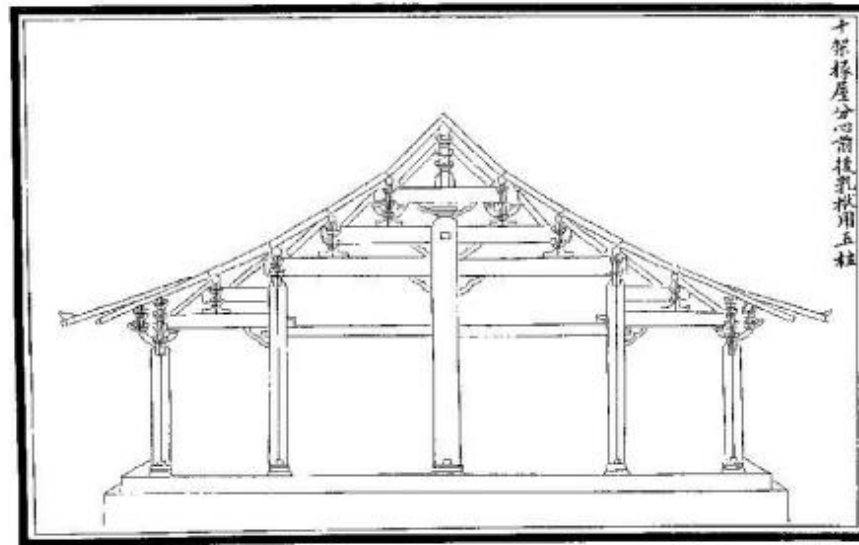
In order to interpret the rules of the *ting tang* section, it is necessary to clarify the rule-based descriptions. Liang (Liang, 1983) reproduced a set of 18 *ting tang* section drawings based on *Ying Zao Fa Shi*, as shown in Figure 65. Together with Li's interpretation (Li, 2003), there are mainly three parts of each description:

First, the depth of the building, measured in horizontally projected rafters (introduced in Figure 87). There are four commonly used types of depth for each section. It could be 4, 6, 8, or 10 rafters. This has been displayed in the floor plan case study diagrams. And the use of rafter to indicate and replace the bay depth is also consistent with the last case study.

Second, the disposition of the beam structure and how the depth is divided. The lengths of beams are also given in rafters. There are three types of beam length: 1-rafter, 2-rafter and 3-rafter beams. Typically, 1-rafter and 2-rafter beams are exceptionally named as *zhaqian* and *rufu* respectively.

Third, the total number of columns. Since each beam is supported by a column, to specify a beam is to imply a column.

Based on the rules defined above, take drawing c of Figure 65 as an example (see Figure 137): The Chinese Pin Yin of the description is *Shijia chuan wu, fen xin, qian hou rufu, yong wu zhu*. The English description is 10-rafter building, centrally divided, a 2-rafter beam in front and in back, with 5 columns. Therefore, the depth of the building is 10-rafter. The depth is centrally divided and it uses 2-rafter beams (*rufu*) both in front and in back and the total number of columns is 5.



c. *Shijia chuan wu, fen xin, qian hou rufu, yong wu zhu*. 10-rafter building, centrally divided, a 2-rafter beam in front and in back, with 5 columns.

Figure 137. The 18 *ting tang* sections (Liang, 1983)

4.2.2 Parametric models with column focus

Based on the understanding to the *ting tang* section, the end product parametric model consists with two major parts: the column part and the roof part. Although they closely connected to each other, it is impossible to consider both parts at the same time at the beginning. Because each part requires a considerable number of variables, parameters and relationships. Therefore, two options are available in modelling: column focus and roof focus. Both attempts will be carried out in this chapter.

In order to clarify the reason of choosing a column focus as the starting point, two revelatory literatures are reviewed as the references. First, in Andrew Li's research of a shape grammar approach to *ting tang* section (Li, 2003), a set of grammar that expresses the *ting tang* sections is provided and this shows the positive possibility to recreate the major structure of these sections. In his study, the rafter concept and the column disposition are expressed in the grammar although the accurate roof curvature is not the primary consideration. This is a reasonable and feasible simplification to the section model. Second, Lin's research (Lin, 2013) on the traditional temples in Penghu County of Taiwan provides an introduction of the constructional sequence of the *ting tang*, *dian tang* and mixed type of the section (see Figure 138). Based on the natural sequence in construction, the parametric construction process can be simulated and inspired. Consequently, the column focus modelling is the starting point.

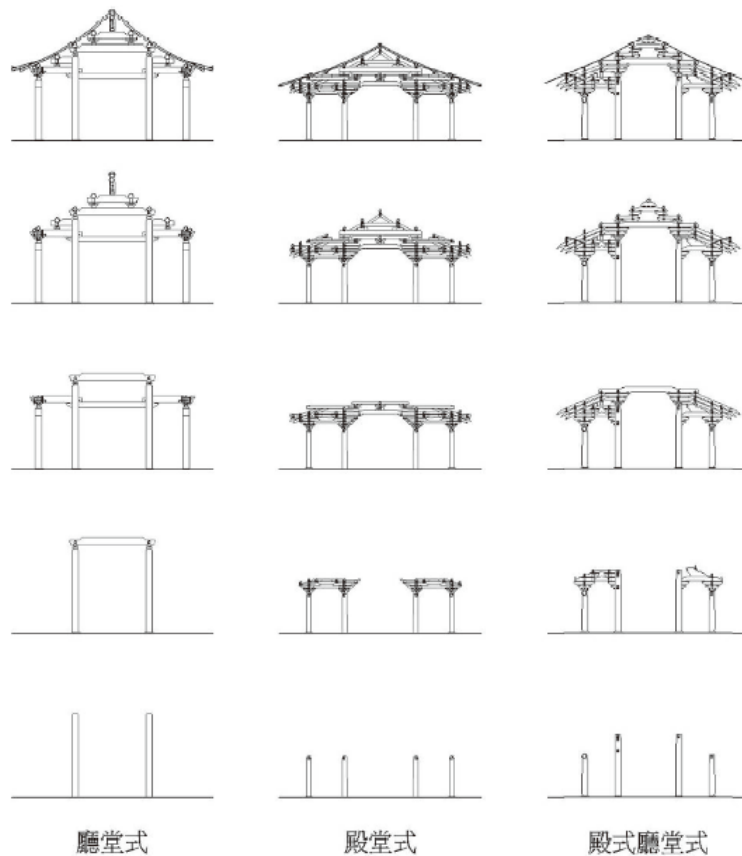


Figure 138. Constructional sequence of the *ting tang* (left), *dian tang* (middle) and mixed (right) type of the section (Lin, 2013)

In *Ying Zao Fa Shi* and Liang's research, eighteen examples of *ting tang* sections (see Figure 65) are catalogued in 4 types according to the depth of the building: 10-rafter, 8-rafter, 6-rafter and 4-rafter buildings. Ten-rafter buildings have the most completed format than the other three types. Thus, if the modelling of 10-rafter buildings is successful, all the other three types then could be subsequently derived. In almost all the examples of 10-rafter buildings are symmetric, and the modelling procedures are as follows. Figure 139 shows an overview. Figure 140 shows the modelling process.

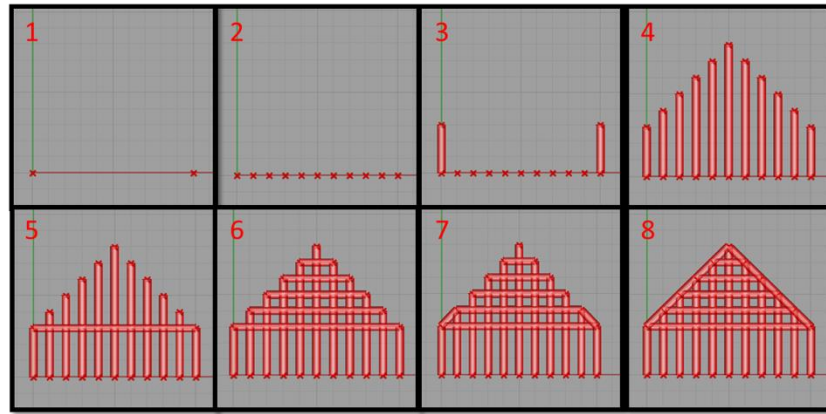


Figure 139. Process 1 to 8 of parametric approach to *ting tang* section

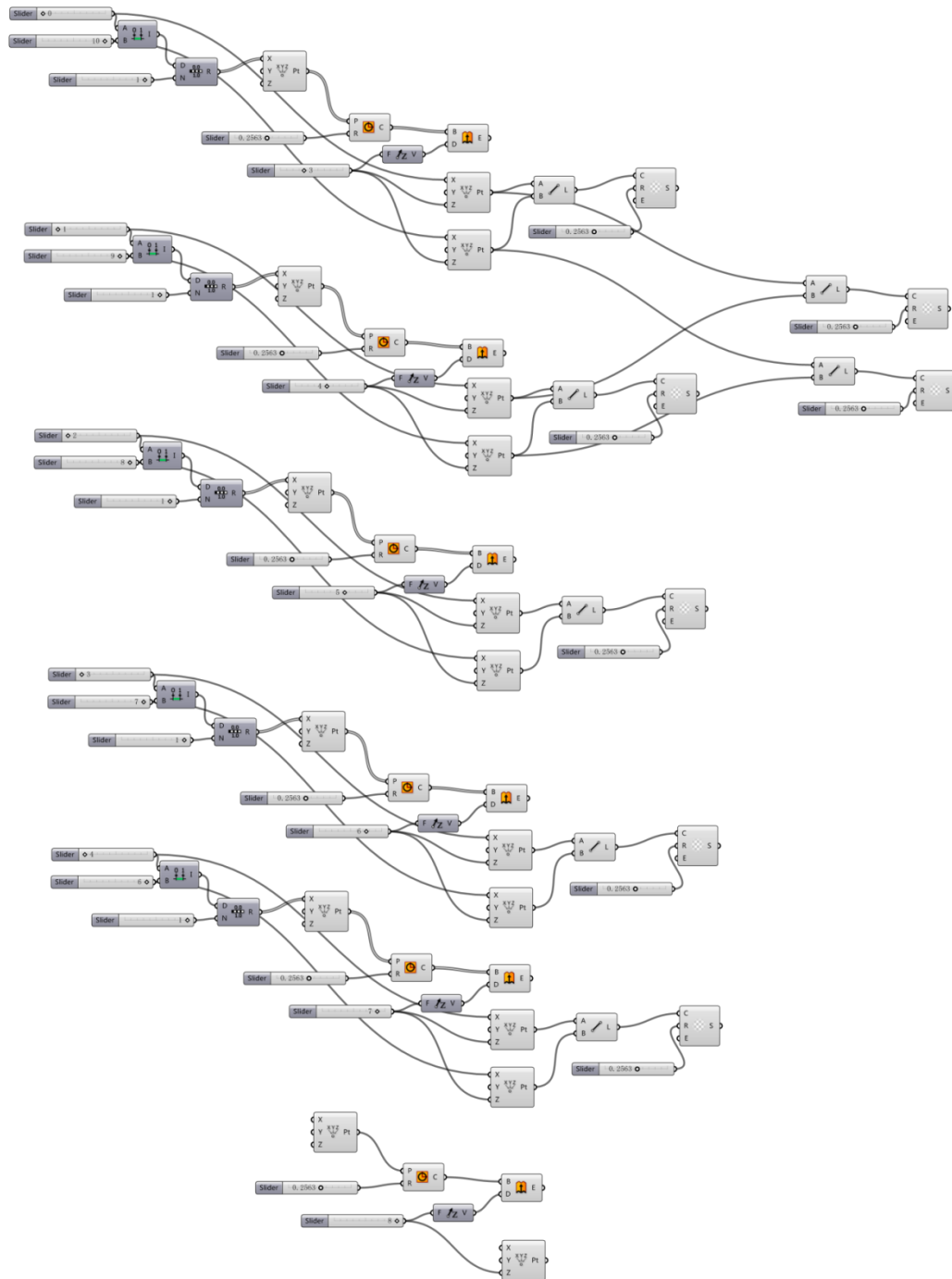


Figure 140. Modelling process of the *ting tang* section

As the model is a 10-rafter building section, and the ten rafters are in equal length, the first step is to make a total depth of 10 units. As this is dealing with proportion, the units are scale-less. In diagram 1 of Figure 139, the two points indicate the positions of the outermost pair of columns (eaves columns).

The next stage is to equally divide the total length into 10 sub-lengths. This results in the eleven points, which marks the positions of all the columns later. The columns are paired working from the outside in. There are totally five pairs of columns but the central column (placed at the sixth point) is single. Here, we organize the column positions in pairs instead of producing all together. The reason for this is that, further on in the process, not all the columns have the same features (such as height or the relationship with the beam and roof). So we need the facility to adjust them individually.

Based on process 2, the outermost pair of columns are built. For initial simplicity and testing, the shape of the columns is simplified as a pipe although it can be later amended to any shape or even with detailed decorations. The height of the columns is also adjustable. To illustrate the process, three units are chosen only for a demonstration. But in reality, the height of the columns may not necessarily be a multiple of the rafter, but it depends on the needs.

Similarly to process 3, each pair of columns is built and the height is gradually increased. The height of each pair of the columns has a range and boundary. But this is not discussed in this attempt since it requires more numerical information.

In process 5, the terminal points of the outermost pair of columns are set as the boundary points of the lowest beam. The properties of the beam such as the height, the position and the length would be automatically generated. In this abstract model, we produce the beam sitting on the corresponding pair of columns without any variation since this is the simplest and most basic structure to study. In practical cases, if necessary, the terminal points of each beam could be adjusted to any point required (as long as the point is on the column).

Similarly as above, the other four beams are produced. The result is five beams corresponding to five pairs of the columns. The central column does not relate to any beam. But until now, the beams are the hypothesis rather than the accurate cases, just in order to complete the main frame of the section. More information regarding the rules of the beam setting variation is required for further expression.

In process 7, there are four points selected to produce each pair of segments of the roof frame (it is known as *ju zhe*, discussed in Liang (Liang, 1983, p. 265), this will be discussed in detail later). In this abstract model, the roof frame is generated by connecting the beam-column-cross-points, therefore it is the simple triangular shape. Later we will show the variation by adjusting the columns and beams. The segments of the roof frame will then be automatically changed following the change of columns and beams without manual modification. But the modelling here does not follow the *ju zhe* definition to build up the accurate roof curvature. Although it reflects the connected relationship between the columns and the roof, it is only a demonstration to complete the major frame. The accurate roof curvature requires more investigation and algorithmic representation.

In the last process, build all the rest of the segments of the roof frame. So far, the basic and complete structure of a 10-rafter building section is finished. It is a basic and abstract modelling attempt with several simplifications and hypothesis. And this attempt is the first bridge between the complicated traditional style section and the parametric concept.

4.2.3 Variations

The following sections will give a few variations (see Figure 141) and discussions. In order to make clear and obvious comparison with the original model, only one parameter (or one relationship) will be adjusted in each variation.

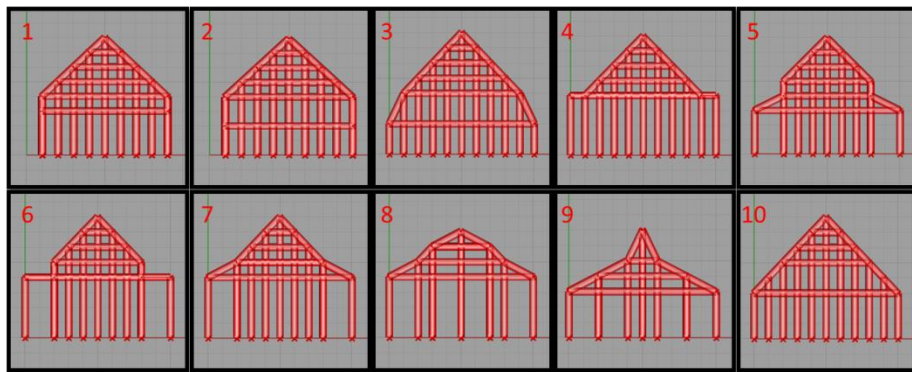


Figure 141. 10 variations of the *ting tang* section model

Firstly, if the outermost boundary (the total depth) of the section is changed, the model becomes an 8-rafter building section with nine columns. This shows the character of remaining the structural relationship but changing the whole scale of the building. Even, in this process, all the beams are kept at their original height levels, although the lowest one is shorten to an 8-rafter depth.

In variation 2, the lowest beam is changed to an even lower position. It could be moved higher, but as there are already several higher beams, it does not need to be changed at this stage.

In variation 3, the height of the outermost pair of columns is shortened. The result shows the lowest pair of segments of the roof frame is automatically changed to a steeper angle. In practical design, this kind of sloping roof could better protect the windows openings which used paper.

In variation 4, the height of the outermost pair of columns is lengthened (which is equal length with the inner pair). The roof frame angle is then followed the change to a horizontal angle. This could simulate those features found in large scale buildings or royal buildings since this kind of design could more easily have decorative parts on.

In variation 5, the penultimate pair of columns is removed. Since all the beams are kept in their original positions but the penultimate beam becomes shorter (equal length as the middle beam), the lowest segments of roof frame changes its angle. This shape (even repeated several times) could simulate the commonly used structure in temple designs. Meanwhile, this model is again an 8-rafter building section.

Based on variation 5, the height of the outermost pair of columns is changed to the same height of the inner pair. So the outermost segments of roof frame changes its angle from tilt to horizontal. And the lowest beam is overlapped with the penultimate beam, resulting in four beams remaining.

Based on the previous stage, in variation 7, we change the terminal point of the outermost pair of segments of the roof frame. The roof frame becomes continuous again.

In variation 8, one more pair of columns is removed. As a consequence, one more beam is removed. This model now becomes a 6-rafter building section and all the segments of the roof frame have different angles. The exact angle could be controlled by the real column heights and the rafter depth (distance between columns).

The same as variation 8, in variation 9 we also remove two pairs of columns. But the height of the existing columns and the rafter depth (distance between columns) are different. The roof frame angle is automatically changed.

In variation 10, we do not change the columns at all but remove the penultimate beam from the model. Similarly, it is easy to remove any beam not in need but keep everything else unchanged.

4.2.4 Discussion

Upon the completion of the first attempt, several aspects are worth discussing. First of all, in general, the basic model is closer to the *Chuan Dou Type*, although we do not specifically consider to express this structural type during the modelling process. But with the completion of the model, this is the natural result. In other words, this is a process that “style follows the parametrics” rather than “parametrics serve the style”. The potential of this model to represent the *Tai Liang Type* requires further tests. And to achieve the goal that “parametrics serve the style” in complexity also requires investigation.

Second, the basic frame and shape of the section is achieved in this attempt. Meanwhile, the control of the parameters is not completely flexible. Thus, the variations have limitation in presenting some certain section styles, such as some certain angles of the roof curvature.

Third, this attempt is based on the symmetric section style, therefore the columns are considered in pairs (except the middle column). This is the most commonly used and basic column disposition. But in some cases, the asymmetric sections cannot be presented using this model.

Fourth, the column height parameter needs to be added into the algorithm in a later attempt.

Fifth, compare this attempt with the rulebook diagrams, it is found that the variation of the beams is complicated. In this attempt, the beam variation is based on the columns, which limits the representation for the real needs. Thus, there is a lack of the summary of the rules to the beams which requires an algorithm in modelling. To optimize this, an algorithm based process is required.

Sixth, since this attempt is column focused, the roof part becomes a dependent variable and therefore its feature is not fully presented and largely limited by the column variations. However, in *Ying Zao Fa Shi*, the rules of the roof are strict and complicated. And the roof is one of the most significant features reflecting Chinese style that cannot be omitted. But since this limitation was already taken into consideration initially, it is possible to find a solution in the later attempt.

4.3 Parametric attempt 2—example based models with roof focus

Following the first attempt, the example based models with roof focus will be carried out in this attempt to focus on the representation of the roof part in the section case study. In the last attempt, the roof details were omitted in the primary consideration and being a dependant outcome of the columns and beams. This attempt will make up this omission and re-consider the section from another focus.

4.3.1 The understanding of the ancient style roof

In *Ying Zao Fa Shi*, the rules to determine the roof curvature is termed *ju zhe*, which in Chinese, *ju* means raise up the curve, *zhe* means break it. In this principle, the roof curvature is determined. Figure 142 is a classical diagram originally drawn by Liang, which gives two examples of how to calculate the roof curvatures with the given

depth and building type. The upper curve is for *dian tang* type using 10 rafters depth. The lower curve is for *ting tang* type using 8 rafters depth.

In this principle, the total height of the ridge purlin is determined first. Then the subsequent individual heights of other purlins are determined respectively in order to make the break line of the roof.

The rise of the total roof height is determined by the building depth, precisely counted between the central line of the front eave-raising tie-beam and the rear eave-raising tie-beam. In other words, it is counted from the central line of the front eave column to the rear eave column (also refer to the floor plan case study for the front and rear eave columns) plus the depth of the protrusion of *dou gong* from the eave columns on both sides. The ratio of the roof height to the building depth is 1:3 for *dian tang* type buildings, and 1:4 for *ting tang* type buildings.

When the height of the ridge purlin is determined, the positions of other purlins can be determined from top to bottom, following the principles in *Ying Zao Fa Shi*. Take 10 rafters *dian tang* type as an example. Make a straight line linking the top of the eave purlin and the ridge purlin (the blue line in Figure 142). This line intersects with the axial lines of the second highest purlin (the green line in Figure 142). Here, the horizontal position of the second highest purlin is 1 rafter from the centre of the building (orange line with arrows in Figure 142). From the intersection point of the blue and green lines, go down $1/10$ of the roof height, which determines the height of the second highest purlin (the red line with arrows in Figure 142). And this is called the first break. Likewise, make a straight line linking the top of the eave purlin and the second highest purlin, and this line intersects with the axial line of the third highest purlin. From the intersection point on the axial line of the third highest purlin, move downwards $1/20$ of the roof height, which is the second break. This is the height of the third highest purlin. Repeat this process and move downwards $1/40$ or $1/80$ respectively, to determine the height of the rest purlins. Similarly, *ting tang* type or other building depth can also be calculated in this method.

The above rules of the roof curvature are from *Ying Zao Fa Shi*, reflecting the Song style. Qing style is remarkably different from it, which inverts the direction of calculation from bottom to top. But this difference does not affect the research process here, since they share the similar *ju zhe* concept in designing the roof but applied in different ways. Considering the complexity, it is feasible to only consider the Song style in this regards. However, if the study here is acceptable, it can also be applied to the Qing style in the future.

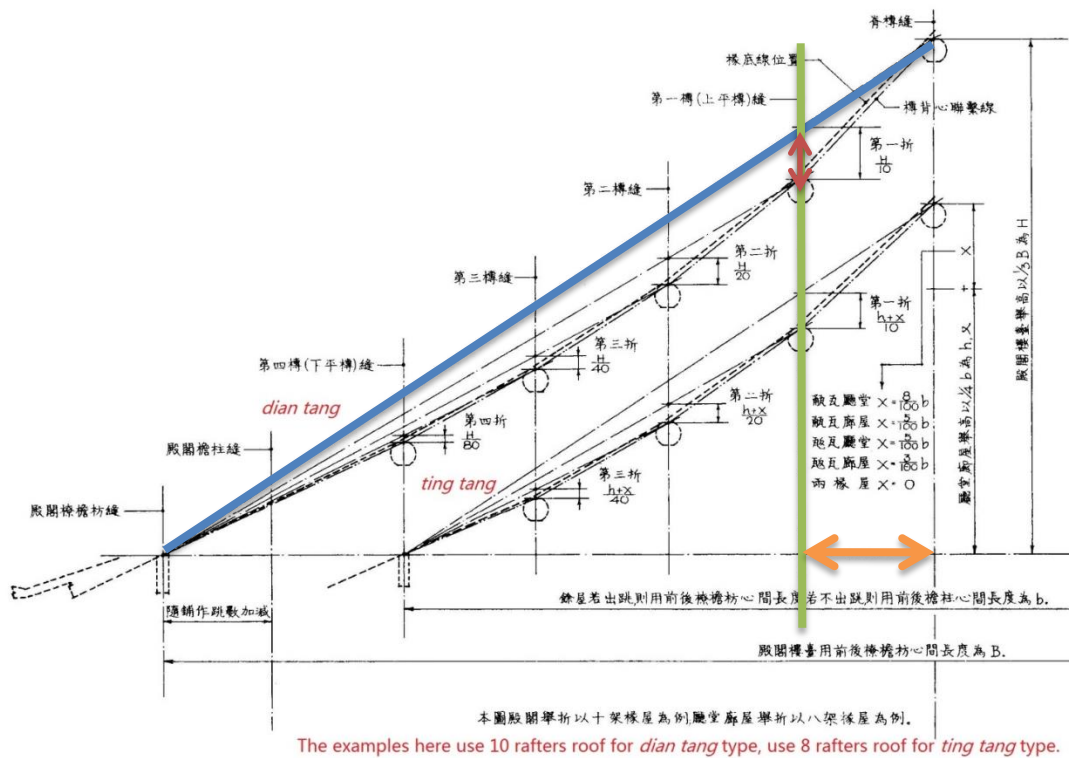


Figure 142. “The principle of *ju zhe*” – the rules for determining the roof curvature, originally drawn by Liang (Liang, 1983, p. 265)

4.3.2 Parametric models with roof focus

Follow the rules described above and illustration in Figure 142, a parametric model can be built up, as shown in Figure 143. As indicated in Liang’s research and drawing, *Ying Zao Fa Shi* defines the roof curvature in the same concept for both *ting tang* and *dian tang* building types, but differ in numerical details. Therefore, the parametric attempt is carried out by considering both types at the same time. But until this stage, in order to make it feasible and clear, the modelling process for the two building types is built up respectively. In the modelling process (shown in Figure 144), for an easy comparison, 10 rafters depth is used as the upper boundary of the building depth for both *dian tang* and *ting tang* types.

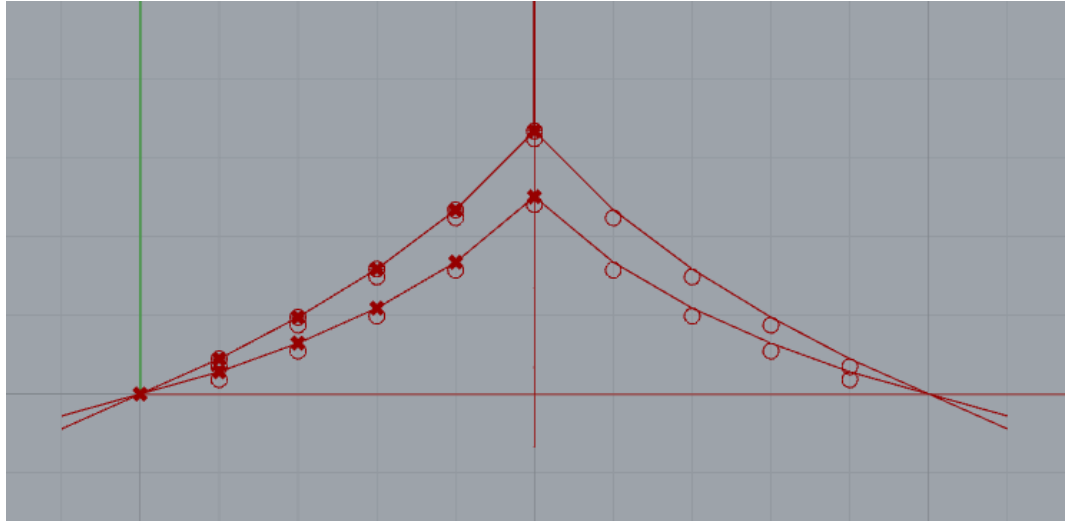


Figure 143. Parametric model of the roof curvatures (upper curve is *dian tang* type, lower curve is *ting tang* type, both 10 rafters)

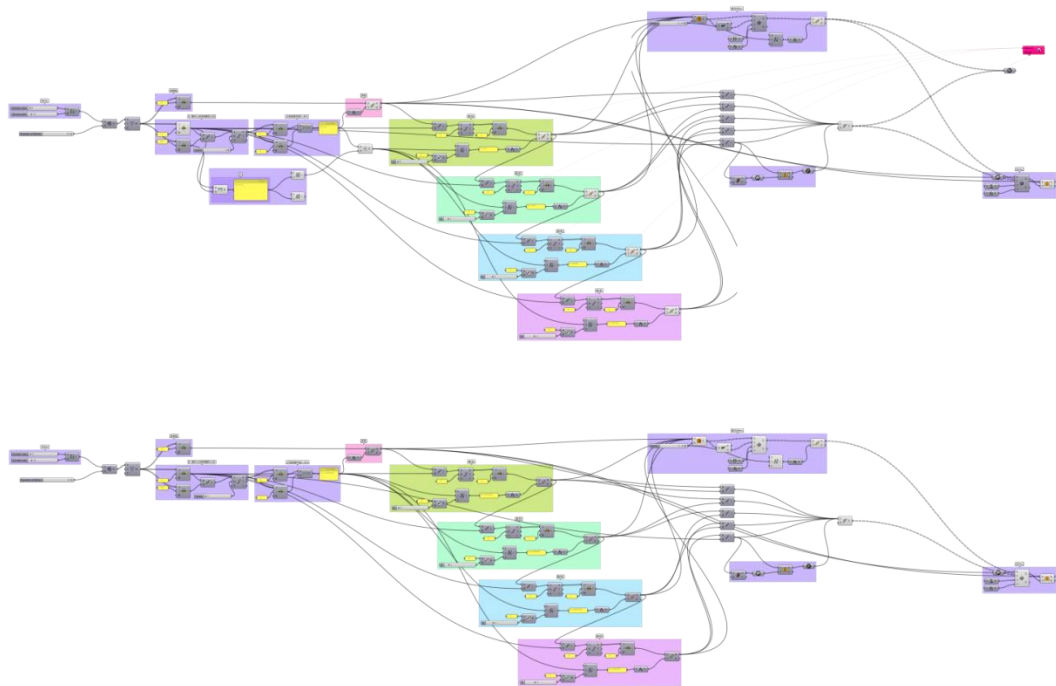


Figure 144. Modelling process of the roofs of *ting tang* (upper diagram) and *dian tang* (lower diagram) types

To build up the *ting tang* type roof, the building depth has a boundary setting of 0 to 10 rafters (see Figure 145). Based on the definition, the building depth counts between the central line of the front eave-raising tie-beam and the rear eave-raising tie-beam, or from the central line of the front eave column to the rear eave column for the *ting tang* type. This value is set as “b” in Figure 142 and in modelling process.

The rise of the total roof height (set as “h”) is determined by the building depth, using the formula in Figure 146. And the modelling process is shown in Figure 147.

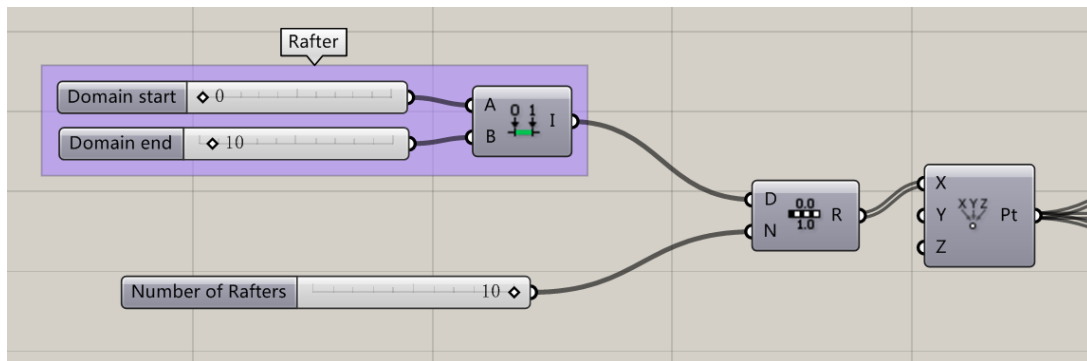


Figure 145. Building depth boundary for *ting tang* type roof

Roof height : building depth = 1:4 (*ting tang* type)

$$h = b/4$$

Figure 146. Formula to determine the roof height (*ting tang* type)

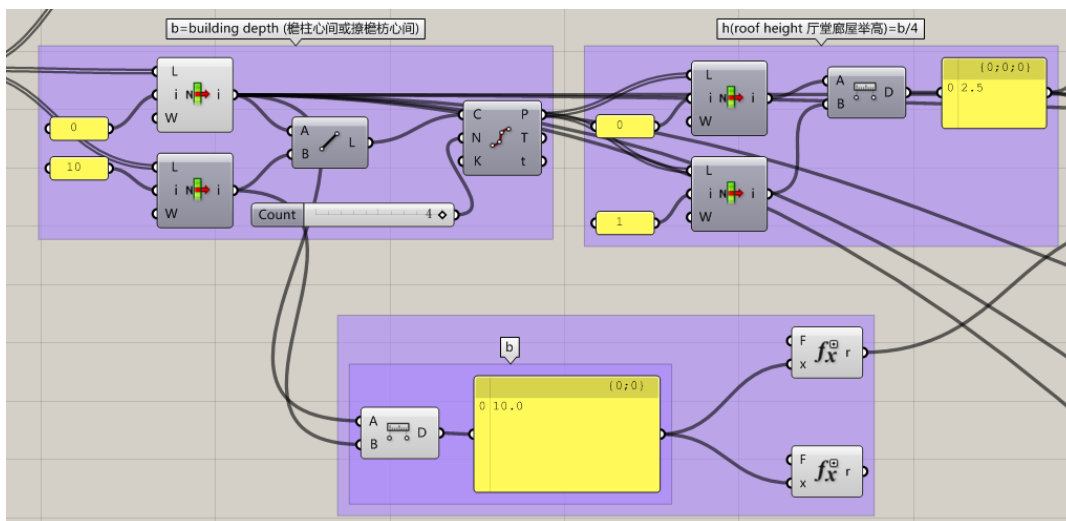


Figure 147. Roof height for *ting tang* type roof

The roof curvature is then built up as defined in section 4.3.1, as shown in Figure 148. Especially, the four breaks are modelled as in Figure 149. This is half of the whole

roof. Since we are considering the standard symmetric roofs, then use the “mirror” function in Grasshopper to mirror the other half of the roof (see Figure 150).

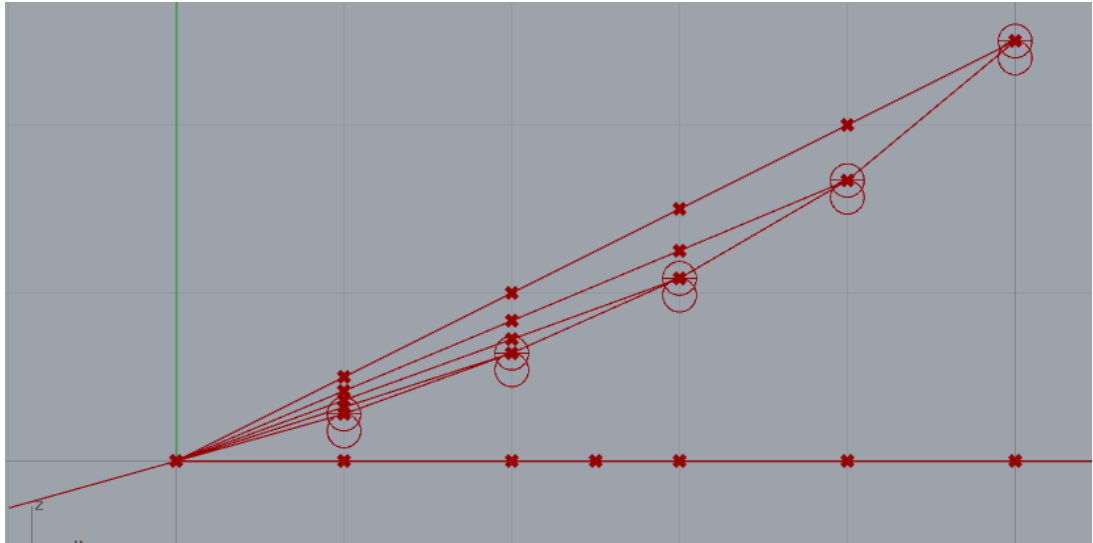


Figure 148. Roof curvature for *ting tang* type roof

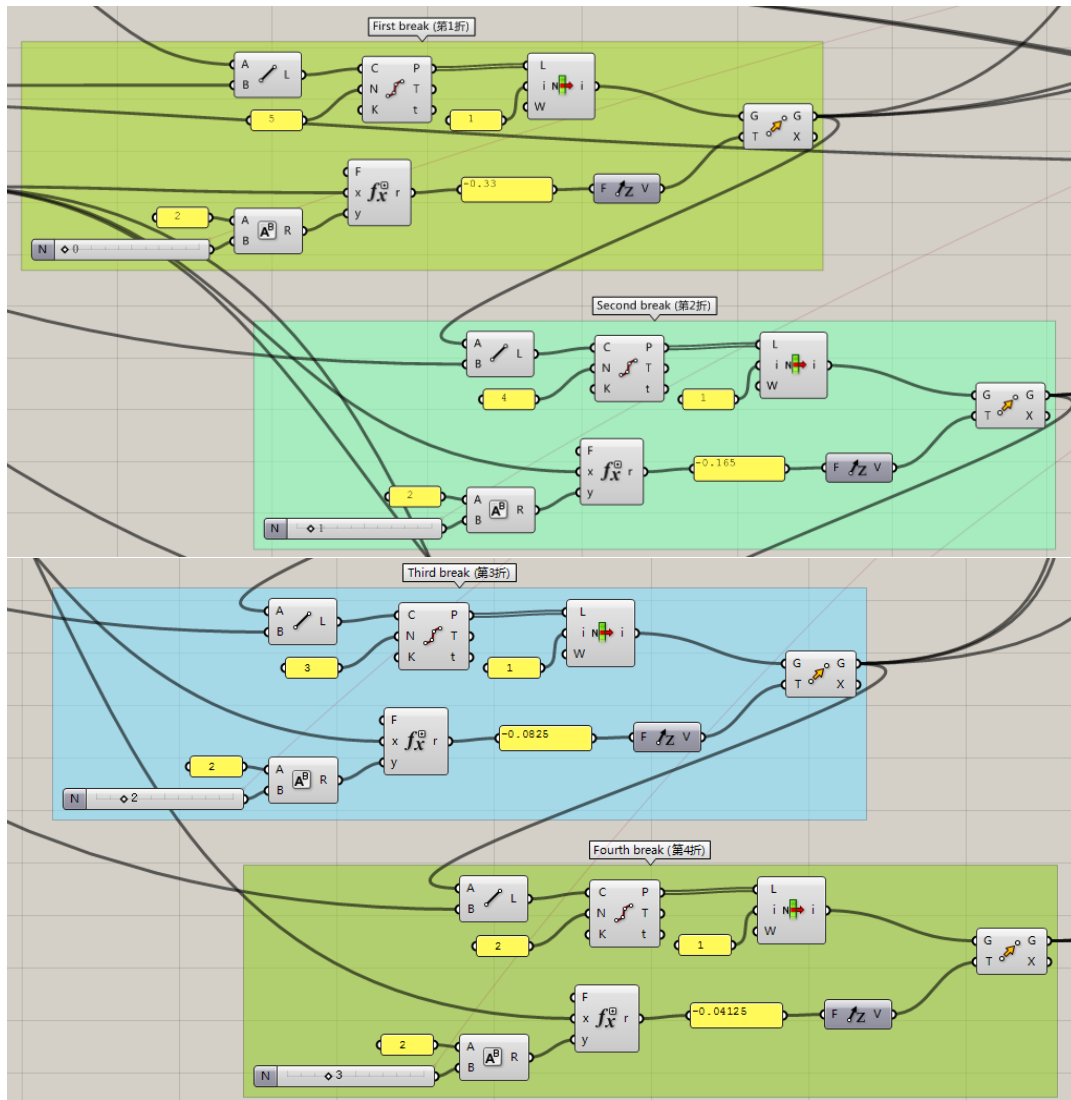


Figure 149. The four breaks of the roof curvature for *ting tang* type roof

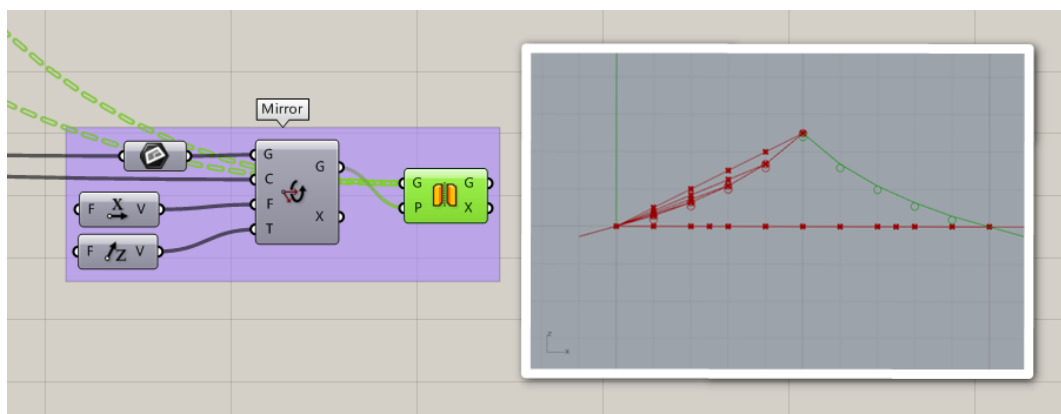


Figure 150. Mirror the other half of the roof for *ting tang* type roof

Similarly, to build up the *dian tang* type roof, the building depth also has a boundary setting of 0 to 10 rafters. Based on the definition, the building depth for the *ding tang* type counts between the central line of the front eave-raising tie-beam and the rear eave-raising tie-beam, or from the central line of the front eave column to the rear eave column plus the depth of the protrusion of *dou gong* from the eave columns on both sides. This value is set as “B” in Figure 142 and in modelling process. The rise of the total roof height (set as “H”) is determined by the building depth, using the formula in Figure 151. And the modelling process is shown in Figure 152.

Roof height : building depth = 1 : 3 (*ding tang* type)

$$H = B/3$$

Figure 151. Formula to determine the roof height (*ding tang* type)

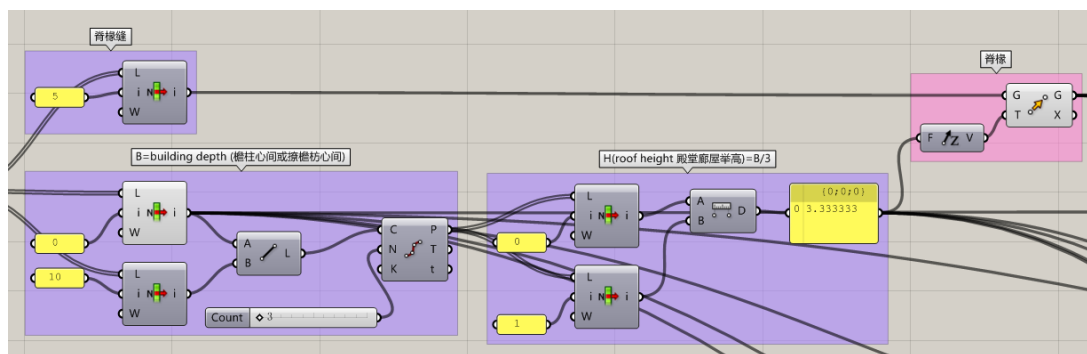


Figure 152. Roof height for *ding tang* type roof

Then the roof curvature is built up also as defined in section 4.3.1, as shown in Figure 153. Especially, the four breaks are modelled as in Figure 154. Again, this is half of the whole roof. Since we are considering the standard symmetric roofs, then use the “mirror” function in Grasshopper to mirror the other half of the roof (see Figure 155).

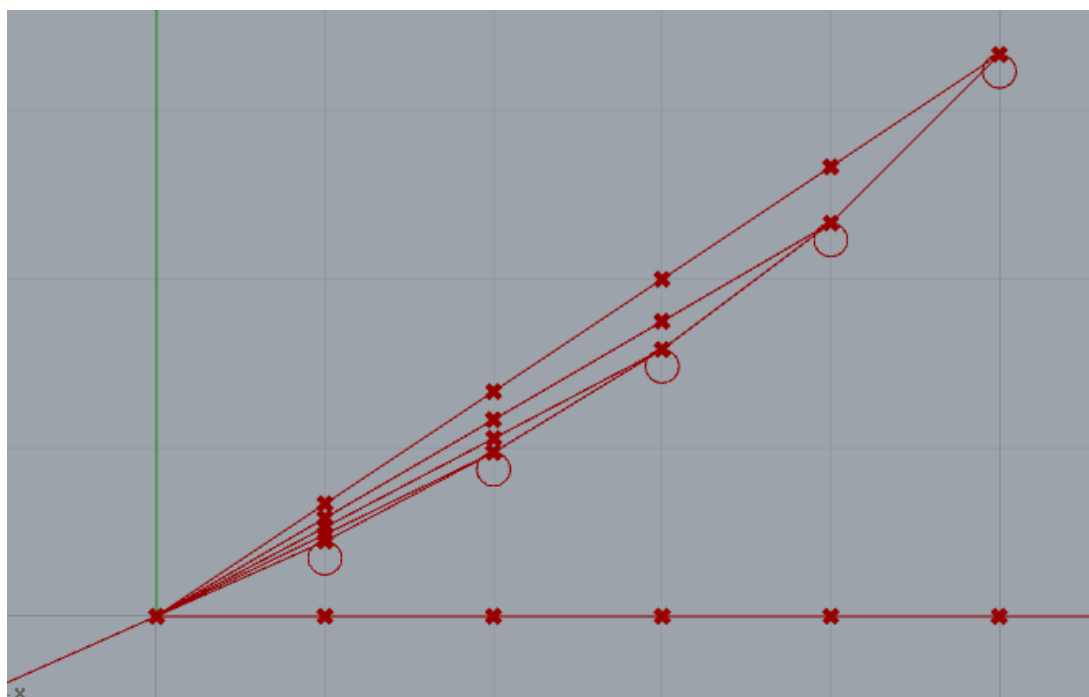


Figure 153. Roof curvature for *ding tang* type roof

163

4.3.3 Discussion

With the completion of the second attempt, there are several aspects worth discussing based on the modelling process above. First, as mentioned before, *ting tang* and *dian tang* types of the roof share the same set of concepts of *ju zhe*. Therefore, they can be considered at the same time. But in this attempt, they are actually modelled separately although the modelling process does share similarities. In the next attempt, these similarities can be further summarized and properly combined to derive one process for both building types.

Second, the modelling of the roofs begins from the rules in *Ying Zao Fa Shi*. Although the rule-book only shows examples of the roof in diagram, together with the text descriptions, a set of rules for the algorithm can be summed up. When building up the models using the algorithm, the outcome shapes strictly follows the features recorded in *Ying Zao Fa Shi*. This can be treated as the first successful step to achieve the goal of “parametrics serve the style” and gradually solve the previous problem of “style follows the parametrics”. On the other hand, one reason of this success is that, only a very small and focused component (roof) is modelled in this attempt. Meanwhile, the roof model is simplified and idealized than the practical cases in the process, which reduces the complexity. To fully investigate the roof, and even, the section, further analysis is required. Therefore, in the next attempt, the algorithm based models will be carried out for further testing.

Third, the variations of the roof of both types were not tested since the parametric models were made based on the examples. But the flexibility and variation is a key essence in parametrics. So this shortage is worth further tests as well.

Fourth, in the next attempt, the current outcome roof models could be utilized as an independent component, inserting into the rest of the section. Also, the algorithm of the roof models can be combined into the rest of the components of the section, forming an optimized algorithm.

4.4 Parametric attempt 3—algorithm based models

Based on the previous two attempts, a feasible approach towards the parametric representation of the section has been gradually developed. The algorithmic rules summarized from both the rule-book information and modelling examples play an important role in the parametric modelling process. Therefore, this attempt will continue to investigate and produce a set of more integrated, efficient and optimized algorithm. By doing so, the parametric modelling outcome will have a substantial progress. Additionally, according to the last two attempts, the columns and the roof can be interpreted as two focused components respectively. This has been proved

that it could significantly reduce the complexity of the modelling. Therefore, this methodology will continue to be used in the new attempt. In order to integrate several components to get the completed section model, the linkage and relationship between these components will be further explored and presented. Through this, the end product will be an ‘authentic’ parametrically integrated representation, rather than a simple assemblage of components assembled in a CAAD software.

4.4.1 Three layers of the section

In the previous two attempts, the columns and the roof have been investigated respectively, which can be the basis to set up the column layer and the roof layer in the section model. There is another important component—*dou gong*, which has been omitted in the simplification. This could be the third component to be considered in this attempt, consisting the *dou gong* layer. Thus, from the bottom to the top, there are three layer consisting a completed section—the column layer, the *dou gong* layer and the roof layer. Pan and He’s research shows support to this concept (Pan & He, 2005). Figure 156 illustrates the three layers with an example of Fuoguang Temple major hall. Although the *dou gong* layer may not necessarily appear in some *ting tang* style buildings, we take it into consideration as if it appears all the time. Whenever a particular building does not need to use *dou gong*, we simply set all the parameters to zero or turn off the relevant parameters to “delete” the *dou gong* layer in the model. In this way, the outcome parametric model will be a widely accepted model of both building types rather than presenting one of the building types only. This is also consistent with the goal to integrate both building types into one set of algorithm. And for this reason, the examples in this attempt will mainly be *dian tang* type buildings since they clearly reflect the features of the *dou gong* layer.

Apart from these, the constructional sequence introduced in section 4.2.2 also shows support to this layer-dividing concept. In Lin’s research (Lin, 2013) on the traditional temples in Penghu County of Taiwan, he provides an introduction of the constructional sequence of the *ting tang*, *dian tang* and mixed type of the section (see Figure 138). From Figure 138, there are three constructional milestones—the construction of the columns, *dou gong* and roof. Simulated and inspired by these natural sequences in construction, the section can be divided into these three layers. Further, the parametric construction process will begin from the bottom to the top.

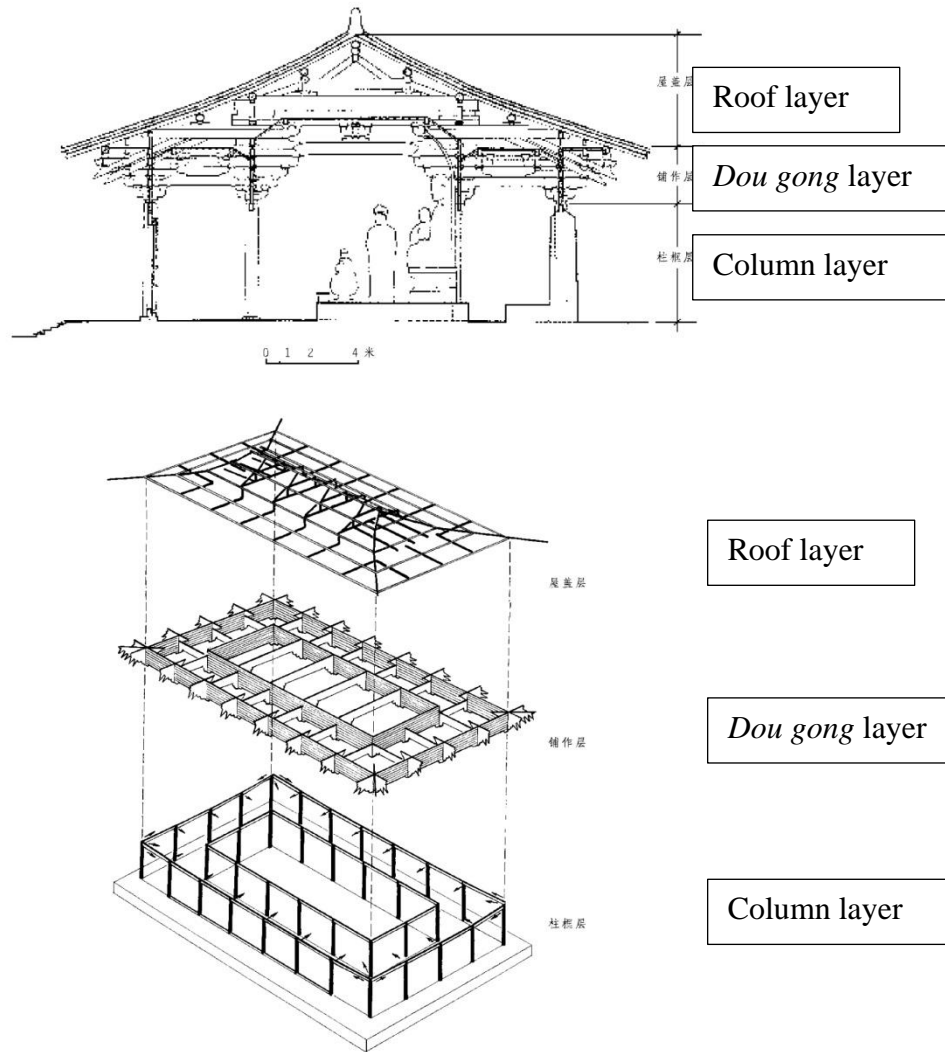


Figure 156. An example of the three layers –Fuoguang Temple major hall (Pan & He, 2005, p. 24)

The linkage between the three layers, and even, the relationship between the section and other parts of the building, is the dominant concept *Cai*. *Cai* has been introduced many times before. At the beginning of the carpentry volume of *Ying Zao Fa Shi*, Jie Li specifies “凡构屋之制皆以材为祖 (in all types of constructional rules, *Cai* is always the fundamental concept)”. As mentioned in section 3.6, a deep and essential relationship that links the floor plan and the section, and even all the rest parts, is the utilisation of the concept of *Cai*. Under this concept, all the parameters and boundaries of the parameters are defined and described by *Cai*, and all the logics between parameters are built up based on *Cai*. In particular, the use of modular units and the distinction of the material levels are the important aspects in this concept. Therefore, the end product will have consistent components although the case studies were carried out one by one. And in the future, any details or decorative parts could be added into this model also with the consistency.

The column positions were exported from the floor plan case study. Then the height of the eave columns is required. Once this is confirmed, this height is also the base line of the *dou gong* layer. By calculating the height of the *dou gong*, the base line of the roof layer will then be obtained. Since the ridge purlin (the highest point of the roof triangle) position is determined by the building depth and rafter (see section 4.3.1), with the rules of *ju zhe*, the roof curvature can then be determined. Through this, the three layers can be built up. In other words, the section frame is modelled. However, unlike the first attempt, only the front and rear eave columns will be modelled in this attempt while the rest of the inner columns will be omitted. This is due to the complexity of the column composition which makes the control of the inner columns unfeasible at this stage. And this is one of the optimized progresses compared with the first attempt.

Ying Zao Fa Shi provides relevant information on defining the columns but not sufficient. Together with the field work measurement done by Liang (Liang, 1983) and research done by Pan and He (Pan & He, 2005), the following algorithms can be summarized. First, the perimeter of the column is six times of the *dou kou* length. The definition of *dou kou* was introduced in Figure 62. Actually *dou kou* is a Qing style module. When Liang, Pan and other contemporary researchers carried out the field trip, they recorded the data using this module for convenience. But this is not a problem at all because there is a certain relationship between the Song module and the Qing module. Recall Figure 63, the relationship between *Cai* and *dou kou* can be linked up. The formulas are shown in Figure 157. In particular, the length of *fen* can be obtained according to the tables in Figure 93 and Figure 94 (and the contents introduced in section 3.3) based on the different grade of the *Cai*. When the column perimeter is confirmed, the diameter and radius is then obtained. Second, the height of the column is ten times of the column perimeter. Third, the column base can be calculated based on the column diameter. In particular, the use of $D/5$ or $2D/5$ depends on the detailed column type. As shown in Figure 158, usually *fu lian* or *fu pen* types column use the number $D/5$, while *yang lian* type uses $2D/5$. After these, the total column height can be calculated.

$$\text{Column perimeter} = 6 \text{ dou kou}$$

$$1 \text{ dou kou} = 10 \text{ fen} = \text{Cai width}$$

$$\text{Column perimeter} = 2\pi r = \pi D$$

$$\text{Column height} = 10 \text{ column perimeter}$$

$$\text{height of the column base} = 3 \text{ fen} + 7 \text{ fen} + D/50 + (D/5 \text{ or } 2D/5)$$

$$\text{Total column height} = \text{column height} + \text{column base height}$$

Figure 157. Formulas of the column layer factors

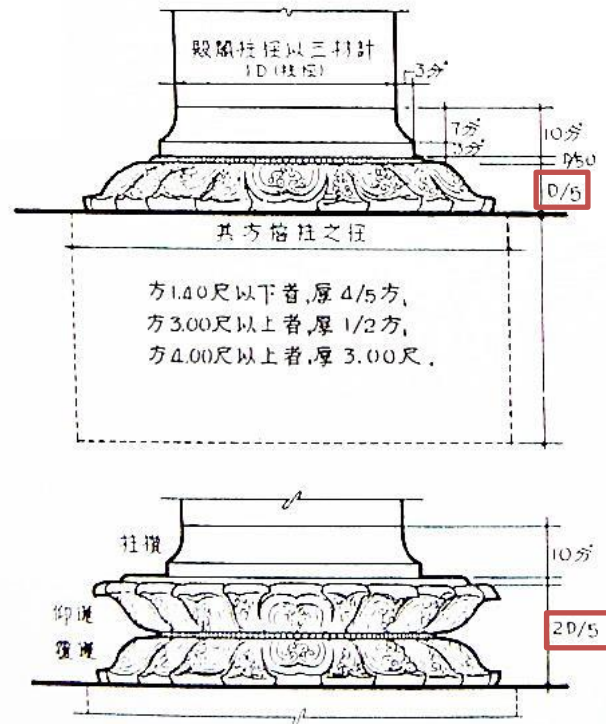
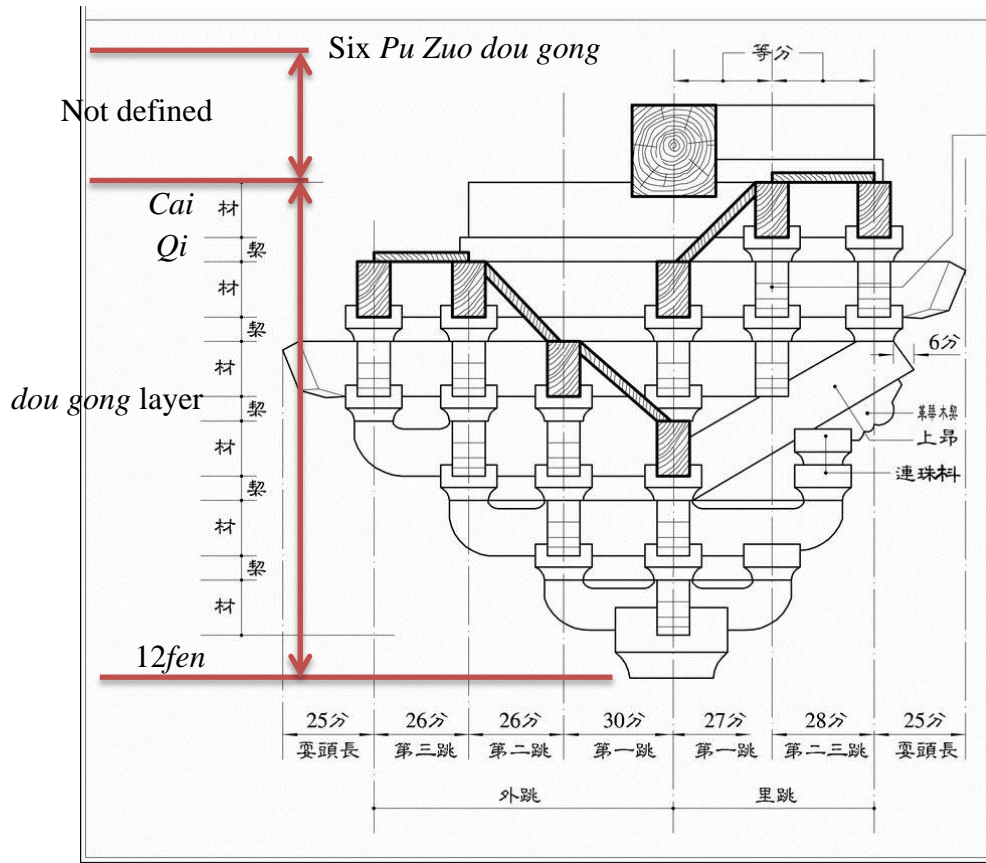


Figure 158. Height of the column base (Pan & He, 2005)

Once the total column height is obtained, this height is also the base line of the *dou gong* layer. Considering the extreme complexity of the *dou gong*, it will be a separate case study in the next chapter. And in deed, the research of the *dou gong* is an extremely wide and complicated topic that cannot be finished in this thesis, nor in the past research. Thus, to continue the progress here, at this stage, we leave the *dou gong* layer as a blank layer without putting the real joints on top of the columns. Instead, we only require the height of this layer to maintain the accuracy of the section frame.

Unfortunately, neither *Ying Zao Fa Shi* nor the architectural historians have clearly summarized this information. So a series of hypothesis are made here based on the set of diagrams that Liang has drawn when analysing *Ying Zao Fa Shi*. These hypothesis are reasonable since Liang's drawings took into consideration his considerable field work. And even if in the future new evidence shows the numerical factors used in the hypothesis need to be updated, it is easy to do so by changing the parameter values in the algorithm.

As shown in Figure 159, in practical cases, the *dougong* and the roof have overlap because of the extent of eave projection of the roof. This brings the ambiguity of the boundary of the two layers. To clarify this, based on Liang's drawing, we assume "the highest point can be measured on the *dou gong*" as the upper boundary of the

Figure 160. Height of the *dou gong* layer (Liang, 1983)

After analysing the typical *dou gong* diagrams drawn by Liang, the height of the *dou gong* layer can be obtained by the formulas in Figure 161. Here *Pu Zuo* is the measurement of the size of *dou gong* which will be further described in section 5.1. Take the six *Pu Zuo dou gong* shown in Figure 160 as an example. $N=6-1=5$. Height of the *dou gong* layer = $12fen + 5 \times 21fen + 15fen = 132fen$. This formula suits to most of the *dou gong*, especially those with the single *ang* (the cantilever arm of the *dou gong*). Although further proof is required for this assumption, at this stage it is a feasible method to determine the height of the *dou gong* layer since the *Pu Zuo* (size of *dou gong*) relates to *Cai*.

$$\text{Height of the } dou gong \text{ layer} = 12fen + N \times Zu Cai + Cai$$

$$N = Pu Zuo - 1$$

Figure 161. Formulas to calculate the height of the *dou gong* layer

The roof layer's calculation was introduced in the second attempt. Recalling the definition, the building depth counts between the central line of the front eave-raising tie-beam and the rear eave-raising tie-beam, or from the central line of the front eave column to the rear eave column plus the depth of the protrusion of *dou gong* from the eave columns on both sides. This value is set as “B” for the *ding tang* type, or “b” for the *ting tang* type. The rise of the total roof height is set as “H” for the *ding tang* type, or “h” for the *ting tang* type, which are determined by the building depth, using the following formulas. Also, the calculation of the length of the breaks was mentioned qualitatively under the *ju zhe* concept. Recall the Figure 142, the length of the four breaks are H/10, H/20, H/40 and H/80 respectively for the *ding tang* type. These values can be summarized in a unified formula, and similarly for the *ting tang* type, as shown in Figure 162. In particular, to obtain the length of the breaks of *ting tang* type, there is a parameter “X”, which varies depending on the detailed categories of the *ting tang* building. The value of “X” is specified as in the five equations.

Roof height : building depth = 1: 3 (*ding tang* type)

$$H = B/3$$

Roof height : building depth = 1: 4 (*ting tang* type)

$$h = b/4$$

Length of the break = $H/2^n \times 10$ ($n = 0, 1, 2, 3, 4 \dots$) (*ding tang* type)

Length of the break = $(h + X)/2^n \times 10$ ($n = 0, 1, 2, 3, 4 \dots$) (*ting tang* type)

$$X = \frac{8}{100}b \text{ (for } \textit{tongwa ting tang})$$

$$X = \frac{5}{100}b \text{ (for } \textit{tongwa lang wu})$$

$$X = \frac{5}{100}b \text{ (for } \textit{banwa ting tang})$$

$$X = \frac{3}{100}b \text{ (for } \textit{banwa lang wu})$$

$$X = 0 \text{ (for two rafters building)}$$

Figure 162. Formulas for the roof layer factors

4.4.2 Parametric models of the three layers of the section

Based on the algorithm described above, the parametric models of the three layers could be built up, as shown in Figure 163. Although we describe the three layers and set up the algorithms respectively, there are close interlinks between them (and also with the floor plan and the *dou gong*). Figure 164 shows the modelling process of the column layer. The front and back eave columns' setpoints determine the positions of the two columns and they have been exported from the floor plan case study.

According to the formulas shown in Figure 157, *Cai* width is another major parameter in determining the height of the front and back eave columns. Then the column height formulas are applied as functions in Grasshopper to get the front and back eave columns as the output. Meanwhile, the height of the columns is also the setpoints of the *dou gong* layer.

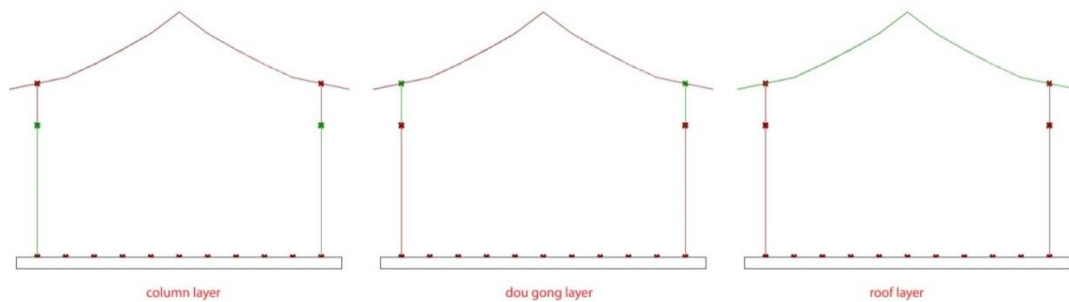


Figure 163. The parametric models of the three layers of the section

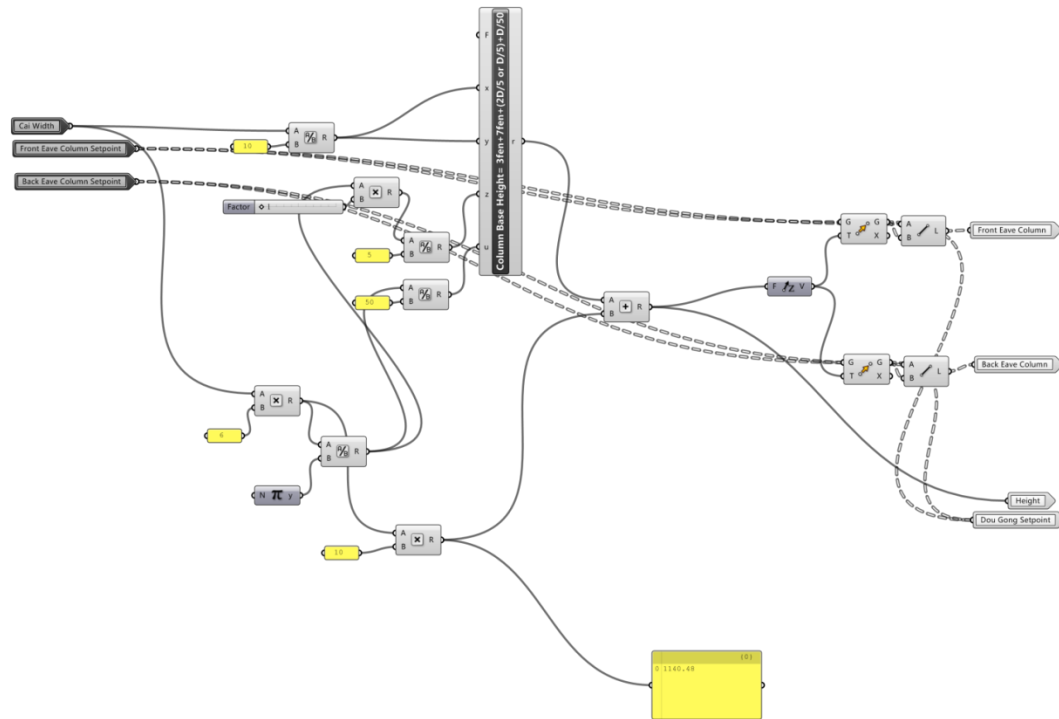


Figure 164. Modelling process of the column layer

On top of the column layer is the *dou gong* layer. According to the formulas in Figure 161, the value of 12 *fen* is related to the *Cai* width, and the height of *Zu Cai* equals to the summation of the *Cai* height and *Qi* height. The parameter “N” is assigned from 4 to 8 since we consider the *Pu Zuo* value varies from 5 to 9, which are intuitively relatively big size *dou gong*. In addition, *Pu Zuo* relates to the grade of *Cai* in presenting the *dou gong* size. Together with the setpoints of the *dou gong*, there are in total six initial parameters to determine this layer, as shown in Figure 165. The completed modelling process is shown in Figure 166. In particular, each group in one pink rectangle presents the *dou gong* with one grade of *Cai*. There are in total eight grades of *Cai*, thus, we build up the algorithm in eight groups. Through this, the *dou gong* layer is represented and the outputs are shown in Figure 167, which are “a blank layer of *dou gong*” and the height of this layer. Meanwhile, the upper boundary of this layer is also the setpoint for the roof layer.

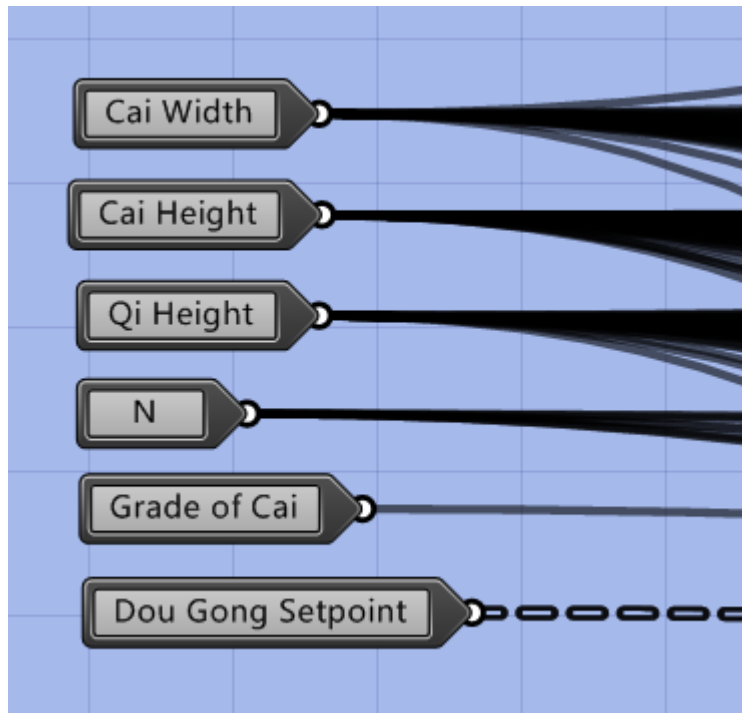


Figure 165. *Dou gong* layer parameters

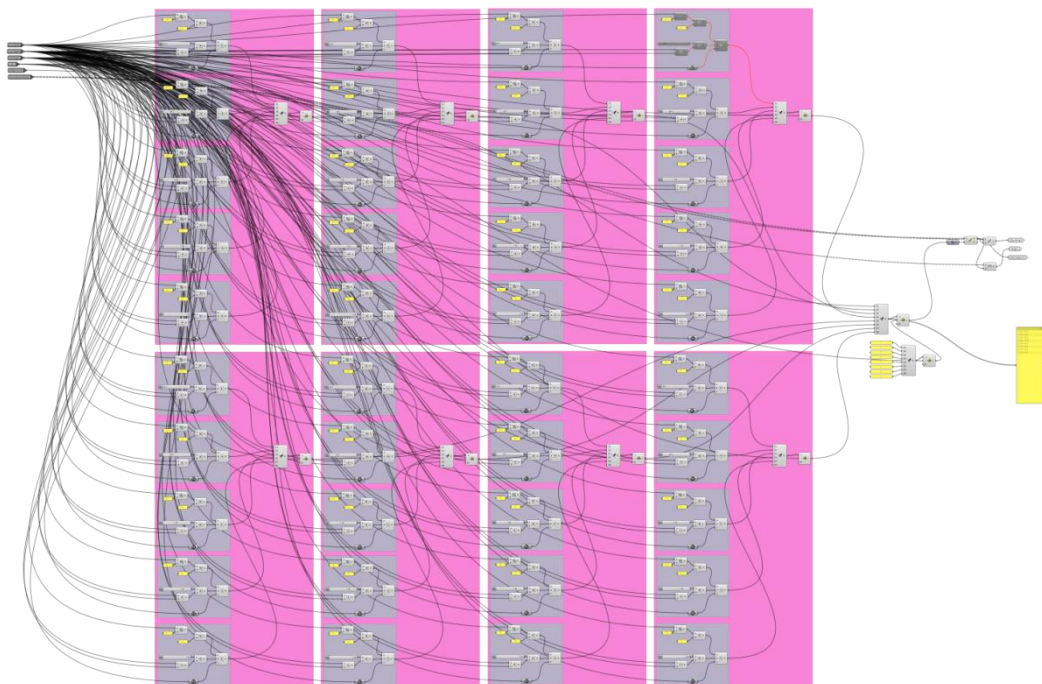


Figure 166. Modelling process of the *dou gong* layer

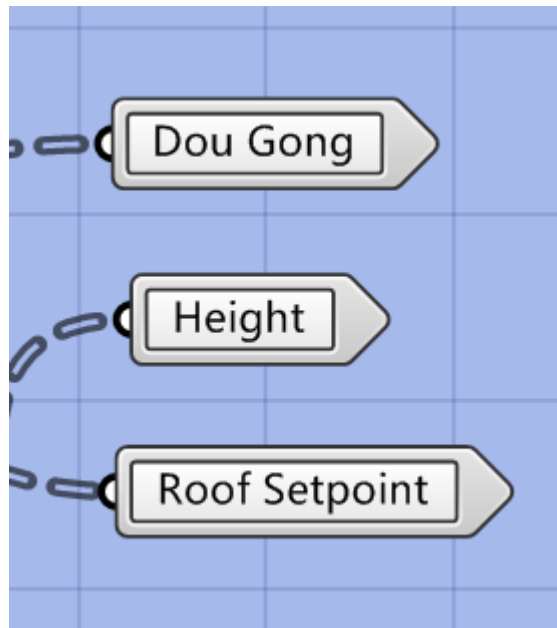


Figure 167. *Dou gong* layer output

Based on the formulas in Figure 162, the height of the roof relates to the building depth, which is determined by the number of the rafter. Therefore, the number of the rafter is an important parameter for both types (see Figure 168). Here, the value of rafter number is set to 10, 8, 6 and 4, but ignore the 2 rafters building since it is not feasible to calculate the roof curvature by *ju zhe* rules with such a small rafter number. The complete process is shown in Figure 169 for *dian tang* type and in Figure 170 for *ting tang* type. The algorithms for both types are built up in four groups to present the four different rafter number values. An example of the rafter number of ten is shown in Figure 171. In each group, the rafter part (see Figure 172 as an example) and *ju zhe* part (see Figure 173 as an example) are built up respectively. In addition, for *ting tang* type, apart from the two parameters same as the *dian tang* type, there is a “X” value as the third parameter (see Figure 174). Therefore, although the major concept of the algorithm is the same for both types, there are two main differences. First, the *ju zhe* rules of calculating the roof curvature are different. Second, there is an extra value “X” for *ting tang* type.

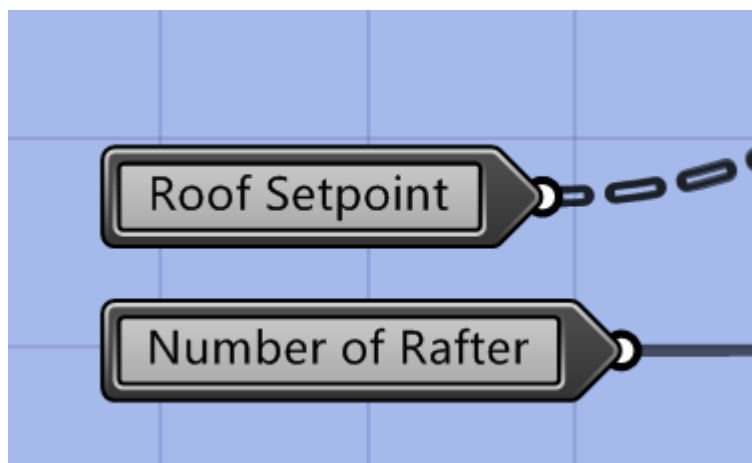


Figure 168. Roof layer parameters for *dian tang* type

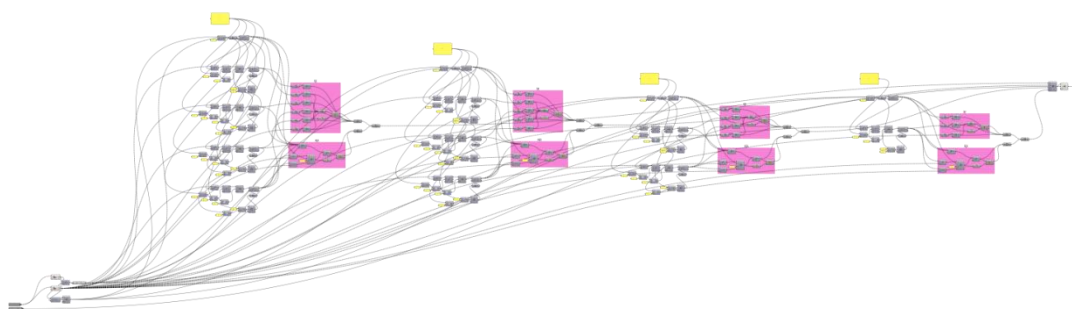


Figure 169. Modelling process of the roof layer for *dian tang* type

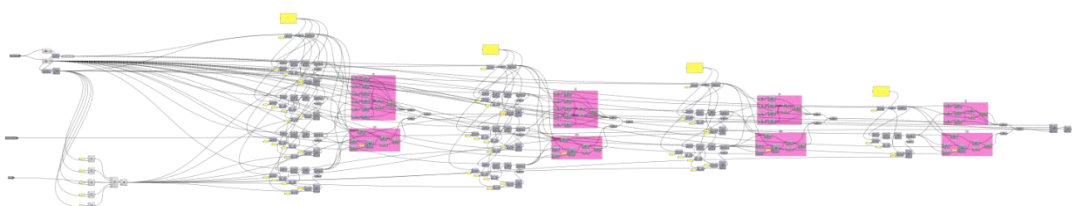


Figure 170. Modelling process of the roof layer for *ting tang* type

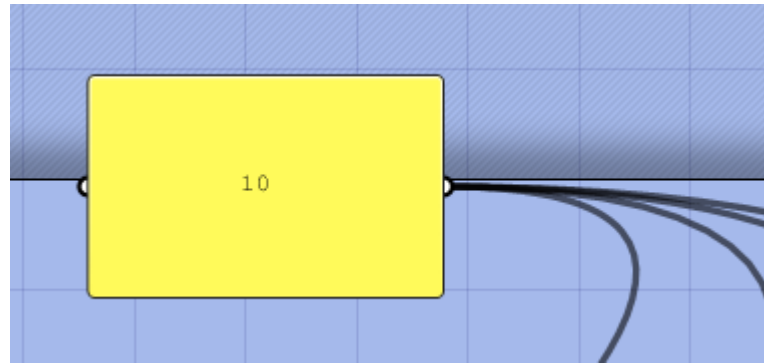


Figure 171. An example of the number of the rafter

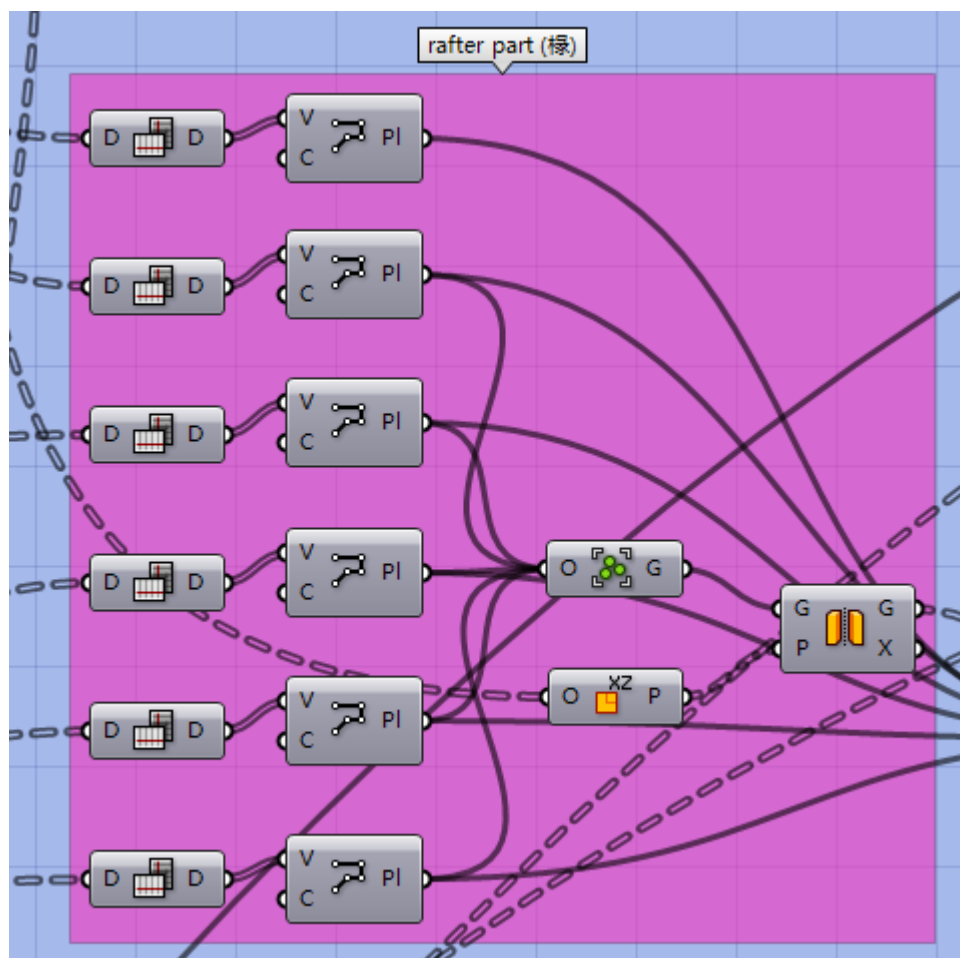
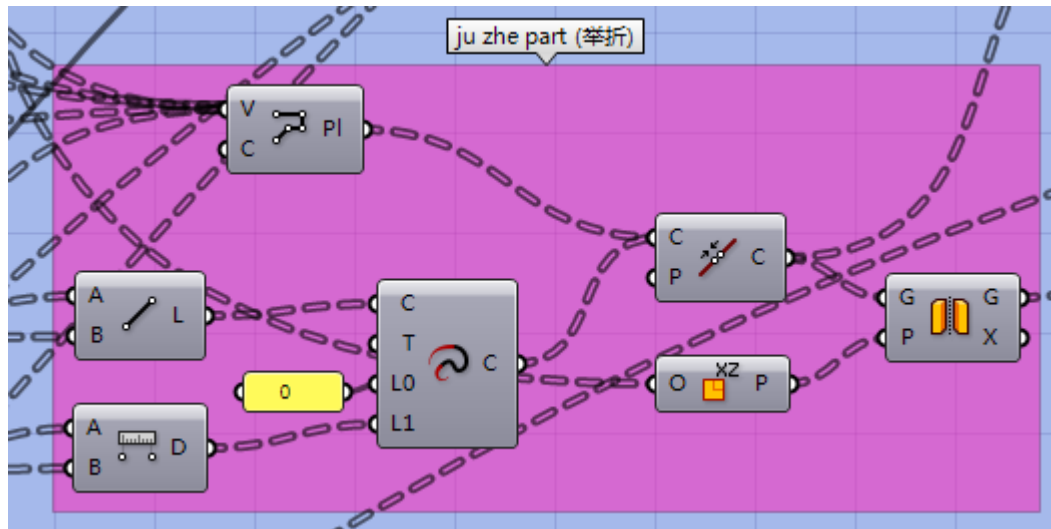
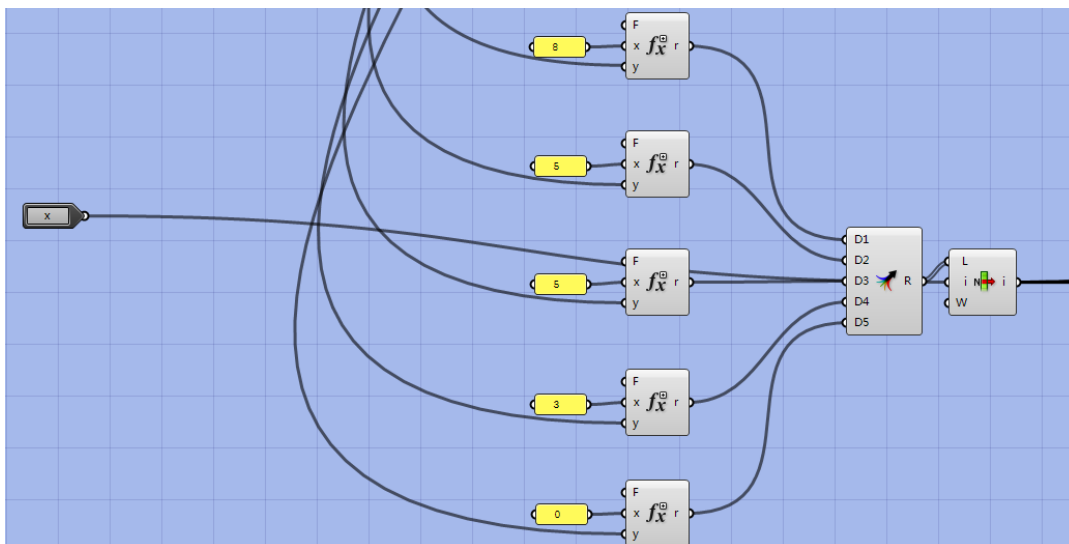


Figure 172. Rafter part for *dian tang* type (10 rafters)

Figure 173. *Ju zhe* part for *dian tang* type (10 rafters)Figure 174. “X” value for *ting tang* type

So far, all the three layers of the section have been established. Similar as in the floor plan case study, the individual algorithms are made as clusters to clarify the input parameters and the outputs (see Figure 175), in a consistent format with those for the floor plan. In this process, the linkage between parameters is set up. Especially for those parameters shared with the floor plan, the links are also bridged. This is not only for the simplification of the control panel, but also an essential preparation for the integrated model which connects the floor plan, section and *dou gong* (this will

be illustrated in Chapter 6). In other words by doing so, the parametric representation will be extended directly from two dimensional into three dimensional.

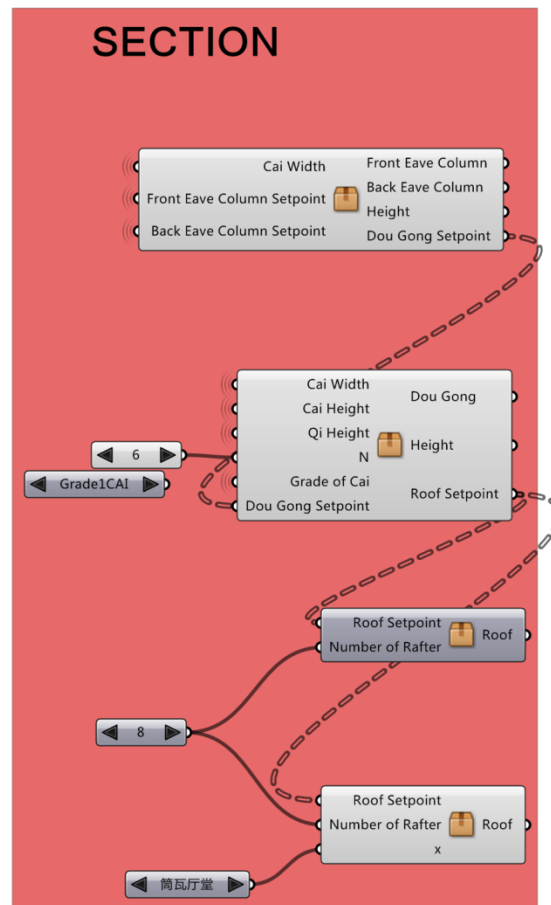


Figure 175. Clusters for the section

4.4.3 Variations

To indicate the power of the parametric modelling, three variations of the dominant variables will be illustrated. First, *Cai* is a key concept throughout the rule-book and modelling in this research. With the variation of the grade of *Cai*, the absolute values of the dimensions of all the relevant components will change correspondingly. In the section case study, this will affect all the three layers. Figure 176 shows the examples of the sections of eight different grades in *Cai*. From the diagram, all the three layers vary following the change of the *Cai* grade, and in turn, the overall scale of the section varies. Second, when the number of the rafter varies, the building depth will follow it to change, and the roof layer will vary as well (see Figure 177). In this situation, the variation does not affect the column layer and the *dou gong* layer. Third, with the different “N” value, the column layer and the roof layer remain the same

while the height of the *dou gong* layer changes, as shown in Figure 178. Therefore, with the different combination of the changing parameters, different output products can be achieved depending on the practical requirement.

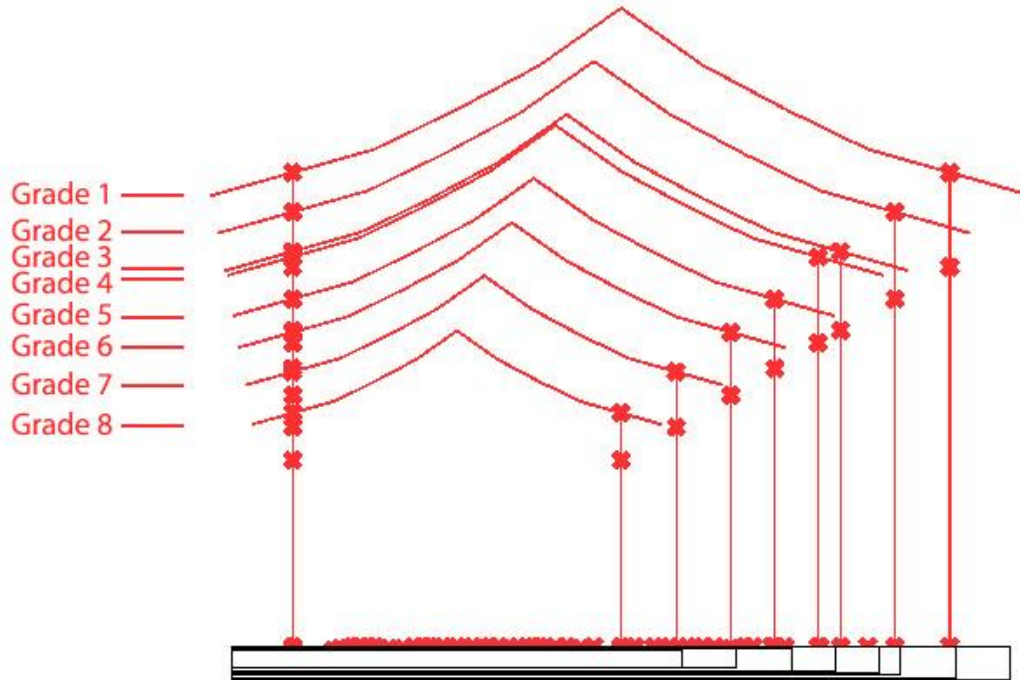


Figure 176. Examples of the sections (N=6, rafter=8) of eight grades in *Cai*

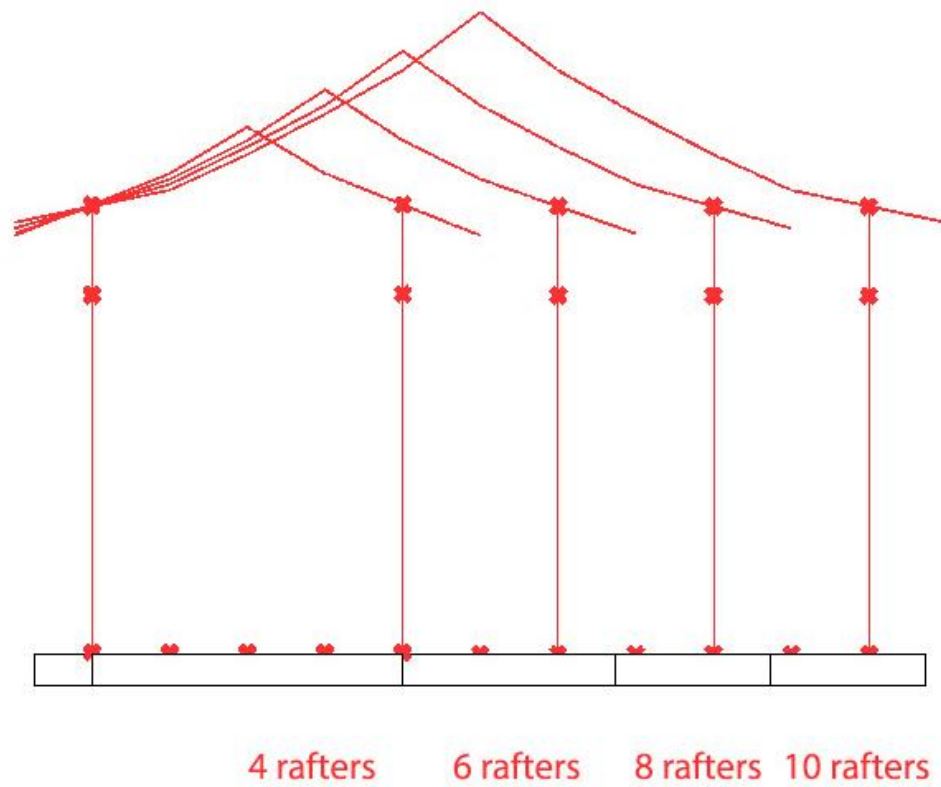


Figure 177. Examples of the sections ($N=6$, grade=1) of different number of rafters

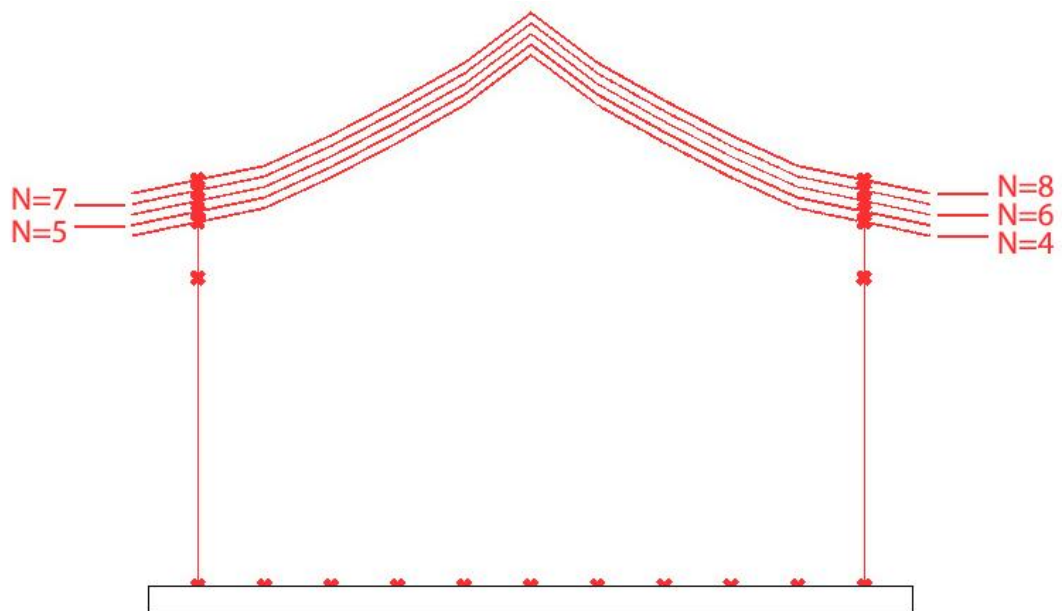


Figure 178. Examples of the sections (rafter=10, grade=1) of different “N” values

4.4.4 Discussion

After the third attempt, several aspects could be analysed. First, the concept of *Cai* connects different components together consistently. It is the rule which determines the building scale and the *dou gong* size. Therefore, it is the essence in the parametric modelling. In addition, if any detailed components are required to add in, or if any built components need to be revised, the work can be carried out consistently with the utilization of *Cai* concept.

Second, it is proved that building the section outer frame with the key features rather than the inner column composition is feasible. In addition, this attempt solves the inaccuracy of the roof curvature happened in the first attempt, but still keep the constructional sequence from the bottom to the top, which is consistent with the practical orders.

Third, the three layers method is also proved to be feasible. It dramatically simplifies the process when trying to build up everything at the same time. Meanwhile, there are still effective and sufficient links between different components. In addition, by doing so, if any changes will be made in the future, it could be precisely allocated without destroying the overall frame.

Fourth, the *dian tang* type and the *ting tang* type sections could be merged together in the most modelling processes. For some components, such as the roof curvature, it is better to consider them separately and then make a selection before the output.

Fifth, the model built up in this attempt roots back to *Ying Zao Fa Shi*, together with a series of reasonable hypothesis, it reflects the Song style properly. Since there is a certain relationship between the Song and the Qing styles, there is a potential to investigate the Qing style section following this attempt.

4.5 Discussion, conclusion and future work

Since Li's Shape Grammar approach to the section was an important reference and a starting point of this case study, it is worth discussing both on the same level. From the study above, the parametric method has three significant features which are similar to shape grammar.

First, a parametric method is systematic and logic. The parameters (building depth, number of rafters, column positions, column height, *dou gong* size, roof curvature and *Cai*) are selected as the variables of the process. Then relationships between these parameters are built into the algorithm and the outcomes are generated. Similarly, the Shape Grammar process is transparent, or, formal, which produces rules just as the rules for reading and writing mathematical statements (Li, 2003).

Second, a parametric method is generative or productive. It produces a design method not by enumerating design options, but by defining how to create the design. This is indicated more obviously in the third attempt. This point is in common with Shape Grammar that we can “demonstrate understanding of a design in concrete ways” (Li, 2003).

Third, a parametric method is both symbolic and graphic. Symbols (used to build the logic algorithm behind the outcome) are more universal medium to assist our thinking and organizing of ideas while graphics (outcome models or images) are more intuitively and a preferred medium of architects. Similarly, Shape Grammar also shows these two characters in its process.

On the other hand, there are also three key differences to Shape Grammar. Firstly, the symbols for Shape Grammar are usually limited to geometrical entities when producing the practical design. Although abstract symbols can be used (Li uses dot and small rectangle when explaining the initial grammars), usually they need to be transformed to geometrical entities to gain the final design. However, parameters used in parametrics could also be discrete or abstract variables. In the study above, the value “N” and “X” are purely abstract mathematical variables assisting the algorithm, and this kind of variables could be set to integer or floating point, which are either discrete or continuous, depending on the requirement. They do not have any geometrical meaning in the output models. But they maintain the logic meaning in the algorithm.

Secondly, in shape grammar, once the rules are defined, they could only be rewritten or repeated in the process of generating the final design. And even if one consequence is changed, the result would be changed. In other words, if we need a different final design, we need to change many steps in the process one after another. But in parametrics, rules can be any kind of logic relationships such as mathematical, functional or geometrical relationships, or Rhinoscript programming, and they are related one to another. Thus if we seek a different final design, we could either change one parameter but keep all the other relationships unchanged, or keep each parameter unchanged but adjust the relationships to change the whole scale or proportion. Normally in practical cases, in order to adapt different local climate, site location, living habits, one type of building need to modify details or structures. But the whole structure of the ancient types of building is very complex. Since each small part is closely related to another one, and a big amount of this kind of relationship exist, it is almost impossible to modify the whole building one by one if changes are in need. By using parametric methods, it is easily achieved, especially if the overall scale and proportion need to be changed. In addition, due to the limitation of the required information or the understanding to the historical rulebooks, inaccuracy may exist in the modelling process. Parametrics maintain the possibility to modify these inaccuracies effectively and easily.

Third, the final result of shape grammar are also geometrical entities whilst for parametrics it could be in a variety formats, such as the numerical output data, depends on the initial parameters and the needs.

Apart from the comparison with the shape grammar approach, there are also several general conclusions. First, this case study is a successive investigation following the floor plan case study. And the conclusions from the last case study could apply to the section case study as well.

Second, in this case study, the attempt begins with the example-based models of different focus. Then the parametric rules and algorithm are summarized. After this, the algorithm based model is established. This process breaks down the complex and difficult goal of parametrics into gradual steps to make it feasible and efficient. Thus, this method could also be applied to other complex component, such as the *dou gong*.

Third, further to the floor plan case study, it is proved again with the section case study that parametric method has advantage in presenting the forms with certain rules and large amount of variations. However, the more complex the rules are, the more difficult to build up the algorithm.

Fourth, the process of achieving a successful parametric representation of complex target lies on two aspects. The one is, a deep understanding of the design concept (such as the understanding of the characteristics recorded in the rulebooks) is necessary. What is more, a proper software interface is essential. This interface should fully fit and support the design and representation needs. Meanwhile, it must be user friendly and easy to learn, control and have flexibility for the users to further develop it. Through this, the parametric modelling process would have a potential to be simplified, widely accepted in practice, and continue to be used in research and design. Otherwise, the complexity and inefficiency may block its application by users. In the above two case studies, we try to achieve this aspect by making groups and clusters. In the future, developing the groups and clusters as new add-ons with specific functions could be a possibility to achieve a more user friendly interface. In the past, the TArch as a plug-in to the AutoCAD can make the AutoCAD makes 2D drawing process simpler and more efficient. And similarly, as an add-on to Grasshopper, Visual Arc also provides an easier and more user friendly option for some certain building types. Consequently, the integration of the modelling process to a more advanced interface could be one of the solutions to complex parametric representation. In other words, when technology or the user skills no longer limit the representation of the design features, the problem of “style follows the parametrics” will be solved. And in turn, “parametrics serve the style” can be achieved.

Fifth, although there are still difficulties, the tradition Chinese architecture, especially the Song style architecture recorded in *Ying Zao Fa Shi*, has already shown the “rule-based” characters, as well as the possibilities and advantages using parametric methods. Especially, the concept *Cai* provides both flexibilities and

variations under certain design rules, which matches the feature of parametrics very well.

Additionally a parametric method has some more advantages. Although the process is a complex act of thinking, the benefit is that parametric design and its requisite modes of thought may well extend the intellectual scope of design by explicitly representing ideas that are usually treated intuitively and being able to explain concepts explicitly is a part of real understanding of design concept (Woodbury, 2010).

There are several future work options. First, the types of the roof were not discussed in this case study since it is closely related to the elevation, which is out of the scope of this research. But as shown in Figure 83 and Figure 84, the roof has plenty of variations and styles, which could be a research target relevant to this research. Second, the elevation could be another useful target since it relates to both the floor plan and the section. Although even without the modelling of the elevation, the three dimensional structural frame can be built up by linking together the floor plan and the section (that will be shown in Chapter 6), the study on the elevation will enhance the findings. Third, the inner columns' composition could be the next step in completing the section details. Fourth, the assumptions made when establishing the algorithms would require further proof to guarantee the accuracy.

Chapter 5 Case study 3—*dou gong*

This chapter is the third case study of the research investigation into the digital interpretation and recreation of the traditional Chinese joint. This is done by turning ancient rule-book information into algorithms and applying these in a contemporary parametric modelling environment. This chapter concentrates on the understanding, representation, digital fabrication and parametric modelling of a typical Chinese joint structure, the *dou gong*. This is a particularly complex aspect in the design and construction of traditional Chinese architecture, as there are many elements to the joint that have a sophisticated relationship with each other, as shown in Figure 179, and there are many variations according to the scale, location, function, decoration and historical period. The joint plays a multi-functional role that covers structure and construction requirements as well as being an essential component of the aesthetic qualities of the whole construction. As Liang points out, “the *dou gong* plays the leading role, a role so important that no study of Chinese architecture is feasible without a thorough understanding of this element, the governing feature of the Chinese ‘order’” (Liang, 1985).

The joint, called the *dou gong*, is described in the Volume Four, Carpentry Chapter One in *Ying Zao Fa Shi* (Li, 1103), which is the bracket set on top of the column and under the beam and the roof.

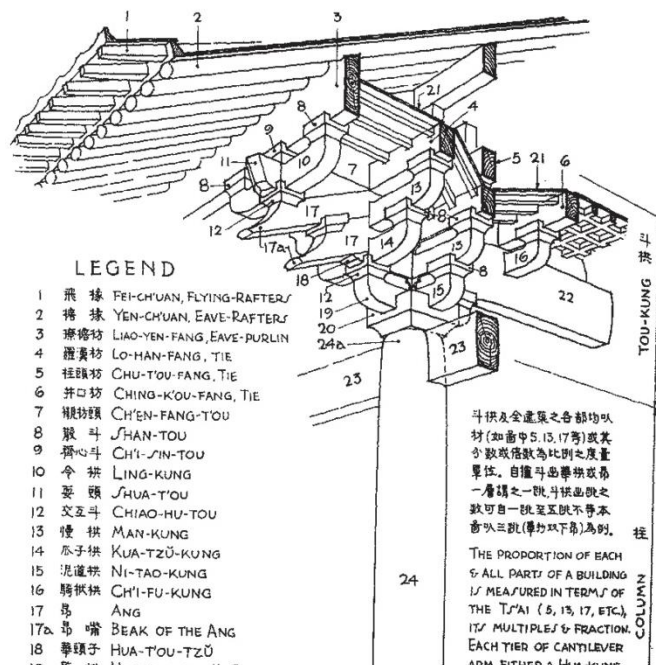


Figure 179. *dou gong* (Liang, 1985)

In this chapter, a brief description of *dou gong* will first be given. Then an initial attempt of top-down method in parametrics will be demonstrated with an unsuccessful result. Based on the analysis of the unsuccessful reasons, an improved proposal is planned that the attempts should be based on the bottom-up method. In order to solve the problem of ambiguity in understanding the joint happened in top-down method, a digital fabrication process is utilized before the parametric modelling could be undertaken. During this process, problems happen in both the digital representation stage and the fabrication stage. Modifications are made to solve the problems. After the success in digital fabrication, three attempts are carried out parametrically by the bottom-up method.

Particularly, in the bottom-up parametric attempts, although ambiguity has been largely clarified by the digital fabrication process, since the outcome is unpredictable at the beginning and the result is completely open, there is no guarantee of success. Thus, the focus is placed on the process that to what extent and how to interpret and represent the joint, rather than the result that to make a model of the joint. Due to the complexity of the joint, there is more than one way to interpret it and build up the algorithm. In order to find out a better solution and more optimized scheme, three different attempts are undertaken with different focus and concepts. When combining the three attempts together, it is most likely to figure out a most optimized approach. However, this brings limitations naturally.

In the first attempt, the focus is to parametrically present the *dou* (the block part) and study on how the parameters and algorithm could be controlled. Therefore one type of *dou* is selected as an example to test. Since the rulebooks were not directly written in parametric language aiming for the algorithmic representation, the key concept in this attempt is to set the rulebooks description as the core, and treat the available parametric techniques as strategy to fulfil the core. In other words, the core is the clear goal of what to be presented based on the rulebooks description and then strategy is based on such goal to find out proper techniques to achieve it. This concept could be called “outcome centred” process. And this requires a large amount of work in technique choice (details will be given in the later sections). In the sense of successfully presenting the selected *dou*, the attempt adequately achieves the goal. Nevertheless, the attempt does not continue to try the same approach on other types of *dou*, neither on other components. Because in such occasion, there is mainly repetitive work or work repeats the same concept that requires extremely excess workload while this does not boost the improvement of the attempt. Even, the prediction could be expected that, in principle using the concept proposed in this attempt, all the individual components could be parametrically presented. Consequently, this attempt is terminated here and focus is moved on to solve the imperfection observed in this attempt, which is, to simplify and optimize the algorithm and reduce the workload in the next attempt.

In the second attempt, the focus is to test parametric presentation on both *dou* and *gong* (the long arm) by studying on how to simplify and optimize the algorithm. In

this attempt, the key concept is to set the available parametric techniques as the core, and test how these techniques could be used to fulfil the rulebooks description. In other words, the primary consideration is the proper parametric techniques and their features, then based on such consideration to find out how the joint can be presented as close to the rulebooks description as possible. This concept could be called “technique centred” process. In the sense of simplifying and optimizing the algorithm and reducing the workload, the improvement is substantial. But meanwhile, this attempt achieves the overall configuration but not strictly the same as the rulebooks description. In order to do so, plenty of detailed range of the controlling parameters need to be inserted into the algorithm. Again, in such occasion, there is mainly repetitive minutiae work which does not boost the improvement of the attempt. Therefore, the attempt is terminated here. Even though, compared with the first attempt, it is predicted that even including all the detailed range of the controlling parameters, the workload could still be considerably reduced, and the algorithm becomes simplified and optimized. In addition, it is also predicted that all the individual components could be parametrically presented in a better approach with the concept proposed in this attempt.

According to these two attempts, both “outcome centred” and “technique centred” concepts are considered to figure out the possibility on presenting individual components. In the third attempt, the focus is shifted from individual components to the overall composition consisted by all components. In this attempt, the layers and positions of *dou* are the initial consideration based on rulebooks description. The algorithm of this process is the key challenge to solve. Once this is confirmed, other components could be added in following the positions of *dou*. Therefore, the detailed demonstration is put on the first process rather than equally describe each component’s position.

In general, although there are limitations in the three attempts, they consistently and effectively figure out an optimized approach to parametrically represent the joint and the methodology utilized here is transferable. After this, a discussion on all the works carried out in this chapter will be provided as well as a direction on how the work could be continued will be suggested to overcome the limitations. Eventually, the relationship of the joint with floor plan and section will be discussed in order to enhance the previous two case studies and link the three case studies together. This will be illustrated in Chapter 6 with the integrated models.

5.1 Description of *dou gong*

In order to investigate the detailed elements of the *dou gong*, an understanding of its development and structure is helpful. From the first appearance of *dou gong* in period of the Warring States (approx. 475BC-221BC), it developed and changed up

to the time when *Ying Zao Fa Shi* was written. This guide outlined a relatively systematic description and established a standard. Later in the Ming Dynasty and Qing Dynasty, it was further developed into a more complex artefact. Apart from the format, the name of the *dou gong* components also changed during the development over thousands of years. Since the two rulebooks are the only available ancient references, the name labelling system used in this research mainly follows the earlier rulebook, *Ying Zao Fa Shi*. In this way the names used in this case study will also be consistent with the broader research work in other chapters.

To gain an overall impression of the joint, Liang's research work (Liang, 2001) is significant. According to Liang (Liang, 2001): The base of the joint is a large square block (*dou*) on the top of the column. There are set into that block crossed arms (*gong*) spreading in four directions. These in turn bear smaller blocks (*dou*) that carry still longer arms spreading in the four directions to support upper members in balance. The jutting arms (*hua gong*) rise in tiers (*jumps*) and extend outward in steps from the large-block fulcrum to support the weight of the overhanging eaves. This external pressure is countered by internal downthrusts at the other ends of the bracket arms. Intersecting the *hua gong* in the bracket set are transverse *gong* that parallel the wall plane. Long cantilever arms called *ang* descend from the inner superstructure, balance on the fulcrum, and extend through the bracket sets to support the outermost purlins. This outer burden is countered by the downthrust of upper interior purlins or beams on the "tails" of the *ang*. The extruding "beaks" of the *ang* easily identify them in the bracket sets.

There are five main functions in terms of the aspects of structural, mechanical and aesthetic functions. Firstly, it is located between the column and the roof as shown in Figure 179, transferring the roof load evenly through the column to the foundation. Second and most distinctive one is to provide an earthquake-resistant function. Since all the horizontal and vertical components inserting into each other follow a prescribed order and rule without any mechanical fixings or glue, its elastic performance can absorb both horizontal and vertical earthquake waves. Previous records show that many traditional buildings with *dou gong* such as the Forbidden City perform very well during earthquake disasters (Liang, 1985). Third and most practical the *dou gong* can support the outwards enlarged roof area to better protect the walls and windows from heavy rains but at the same time prevent the blockage of the daylighting from the pendulous roof edge. It is especially important because in ancient periods traditional windows are made of paper and the main structure of the buildings are made of wood, both require water proof mechanism. An example discovered by Liang (Liang, 1985) is Fuoguang Temple major hall (built at 857), the extent of eaves project about four meters out from their supporting columns. "Their importance in sheltering the wooden structure from weather damage for over 1100 years is, they throw away from the building the rainwater that courses down the tile troughs of the concave roof" (Liang, 1985). Fourthly, the *dou gong* also extents inwards to shorten the span of the beam and *fang* so the stresses on the beam and

fang are reduced. Apart from the structural and mechanical functions, the *dou gong* also has aesthetic functions, which are not dispensable although it is normally hidden under a large roof. Factors such as the size and complexity, as well as the style and colour of the *dou gong* indicates the level of importance of the building itself, and that further implies the social status and richness of the building owner. For example, the royal style *dou gong* was strictly forbidden in civic buildings in ancient dynasties.

Depending on the location within the building, there are mainly three types of *dou gong* as shown in Figure 180: *Zhuan Jiao Pu Zuo* (*dou gong* at the corner, connect with column, support the corner beam and roof corner, and this is the major structure component), *Bu Jian Pu Zuo* (*dou gong* not at the corner, not connect with column, this is the assistant supportive component) and *Zhu Tou Pu Zuo* (*dou gong* not at the corner, connect with column, this is the main support of the eaves load). The measurement of the size of *dou gong* is *Pu Zuo* and normally there are four to seven *Pu Zuo dou gong*. Within each *dou gong*, fifteen key elements can be summarized in three categories: *dou*, *gong* and *ang*. *Dou* is the blocks under and to give support to *gong*, or on top of and at the two ends of *gong* in order to provide vertically extension to an upper layer of the *gong*. *Gong* is the long bracket arm supported by *dou* and to extend horizontally the area of the whole structure. *Ang* performs as a balance lever inside the joint. Different types and *Pu Zuo* of *dou gong* has different prescribed order to insert serials of *dou* and *gong* and other minor elements together. Details of the fifteen key elements and the overall assembly orders are illustrated in Figure 181. The example used in this case study is a five *Pu Zuo dou gong* in Song Dynasty based on *Ying Zao Fa Shi*, since five *Pu Zuo dou gong* has the suitable complexity which clearly shows all the major components, but does not have too many repetitions of each component. Therefore it is used as a typical case study example for the research at the starting point. Once it is clearly understood, other types and sizes of the joint could be similarly treated.

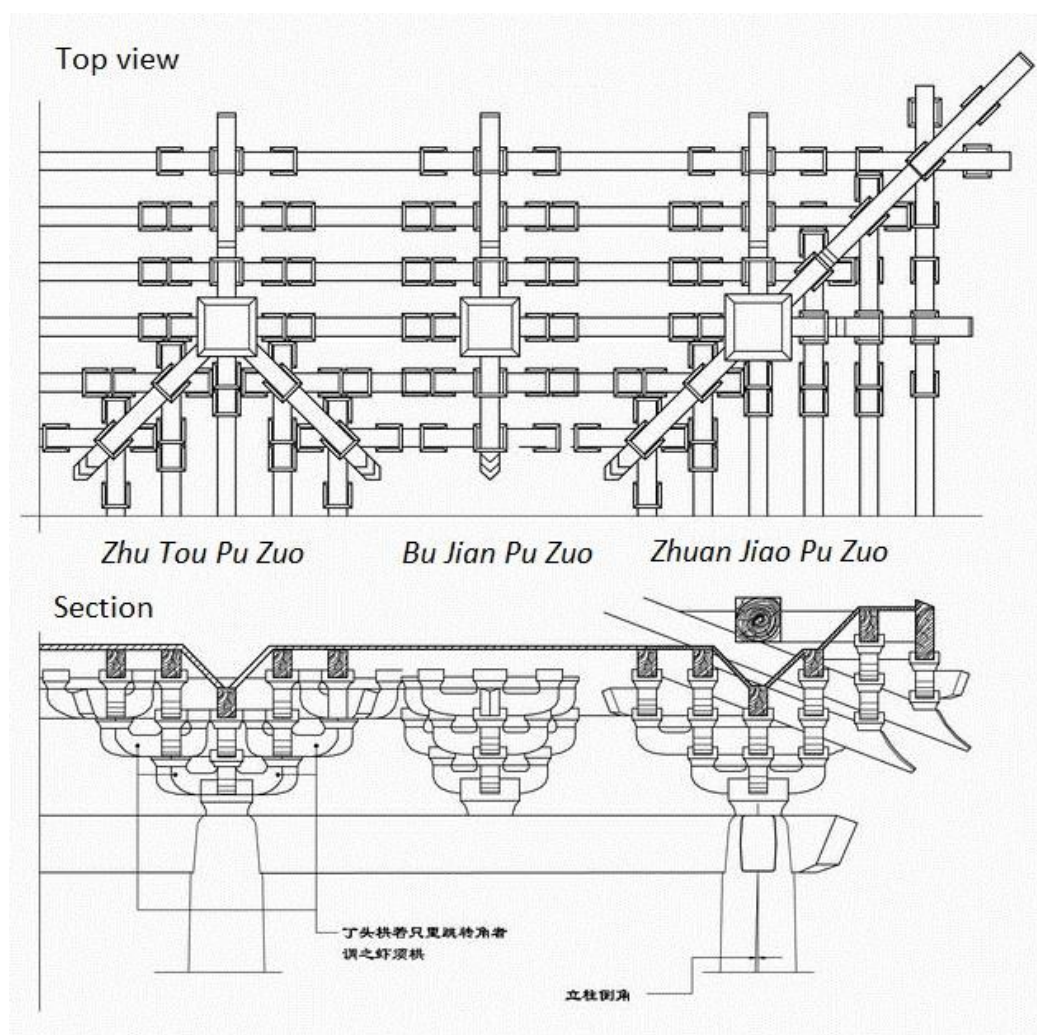


Figure 180. Three main types of *dou gong* (Liang, 2001)

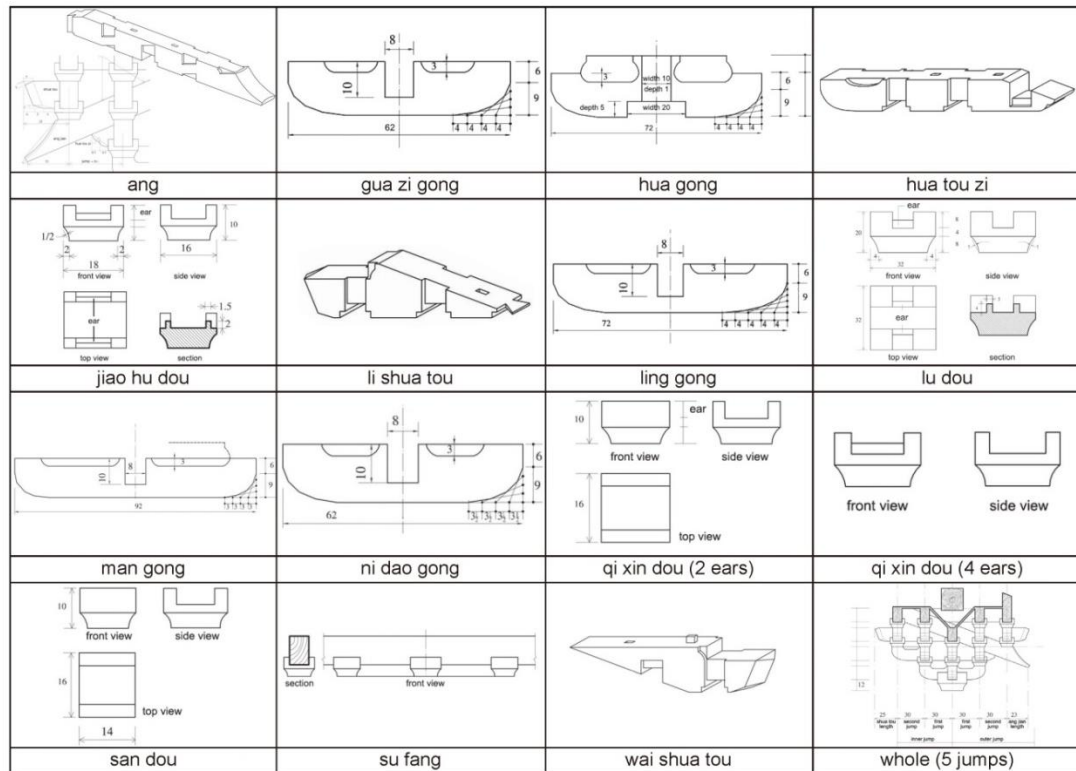


Figure 181. Components of the *dou gong* (Edited by the author based on Liang's drawings) (Liang, 2001)

5.2 Top-Down method in parametrics

To understand the *dou gong* parametrically, two approaches can be taken. First, the *dou gong* is treated as a whole rather than focusing on each individual element and the modelling process concentrates on building up the whole structure and setting up the position of all the elements. The detailed elements will be dealt with later. This is the top-down method. The second involves the construction of each element first and then connecting them together. This is the bottom-up method and the focus of this case study, which will be discussed in detail after the top-down method.

Following the initial description given above, a graphical representation is made as shown in Figure 182 using Grasshopper. Since the main structure of *dou gong* is overall doubly symmetric, in order to construct the model efficiently, one fourth of a complete *dou gong* is built up. By mirroring twice, a complete *dou gong* could be carried out. This is a conceptual model which is based on a commonly used concept of the tree branches. Several layers of the tree branches grow and expand outwards, which generates the extended tree canopy. In this process, the iterative layers and extension of each layer are the key factors for simulating the bracket set. To achieve this, first of all, a series of points are set up along the Z axis. This provides the initial partition of the layers, which are the basis for *gong* (the long arms). The number of

the layers is controlled by an input slider which can be changed based on the need of layers. The Graph Mapper is an effective method in the controlling. Then the parabola function is selected to generate all the points locating the tree branches (representation of *gong*). The strongpoint of the parabola function is to be able to easily define all the layers together. But from the later process, it is found that this might lead to the loss of control of the branches shape within each layer. To improve this shortage, the Gaussian function is introduced to replace the parabola function in this process. As shown in Figure 183, the shape of the branches is closer to the *gong* described in the rulebook. Following this, a rectangular grid of points is set up within each layer. The area of layers reduced gradually from the top to the bottom along the Z axis. Here Path Mapper is used to arrange the location of points within each layer. Then, building up all the branches by lofting the curves based on the grid of points. In this process, it can be noticed that although the position of the *gong* (tree branches) is defined, the position of the *dou* (the small rectangular blocks) is omitted without a clear definition and consideration. But actually from Figure 182 top view, it is shown that the small square of grid within each layer could be used as the position of *dou*.

From this experiment, three points of merit can be noted. First, the layers and extension within each layer are achieved. This is a basis to recreate different scales of the joint without the need for another set of logic definitions. In addition, this attempt can fulfil some of the main functions stated in the rulebook, such as the potential to enlarge the roof area both outwards and inwards. Thirdly, the configuration can be adjusted by controlling all the input parameters. This enables the possibility of the achievement of the aesthetic function of the joint, that is, to treat the joint as a pure classic decoration. And indeed, since the Ming Dynasty, the structural function has become less important due to the development of other constructional technologies while the aesthetic value became more emphasized.

On the other hand, several problems were observed. The accurate shape of the joint is not represented well in the experiment; as well as its volume, an extra set of logic relationship which defines the precise shape and volume of the joint is needed. This is necessary to guarantee the achievement of other important functions of the joint. In addition, the accuracy of each element of the joint is also omitted. Apart from these matters, there is a key component, *ang*, which acts as a lever in the function, omitted from this model. The above problems lead to the adoption of the second approach of the bottom-up method in the following sections.

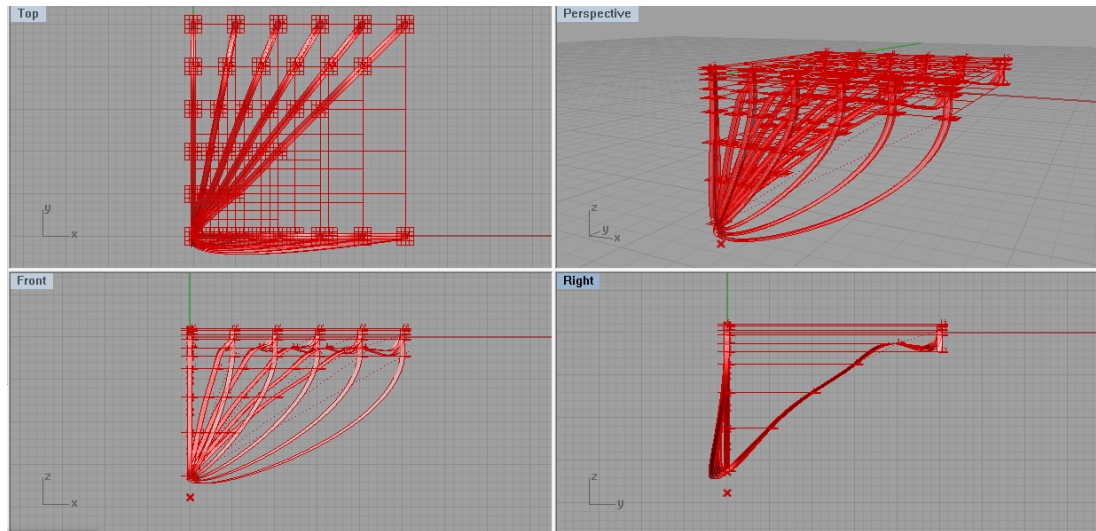


Figure 182. The top-down approach of *dou gong*

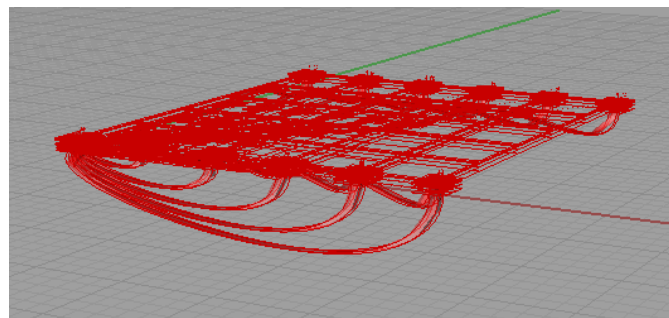


Figure 183. The top-down approach of *dou gong* using the Gaussian function

5.3 Bottom-Up method in digital fabrication

The second approach is the bottom-up method which involves the construction of each element first and then connecting them together. Before the parametric attempts can be carried out, the digital fabrication process is taken in order to clarify the ambiguities in understanding the *dou gong* and better solve the problems happened in the top-down approach.

5.3.1 The digital representation of the *dou gong* components

Based on the description of the *dou gong* elements in *Ying Zao Fa Shi* and Liang's drawing shown in Figure 181, a set of fifteen digital models are generated. The same as the last two case studies, since the digital model is parametric, the real units are

omitted. Instead, all the measurements are made based on the proportions, or in other words, the relationships between each segment. With the proportions, eight grades of the buildings have different units and absolute values to use based on the concept *Cai*.

Due to the complexity of the *dou gong*, the main issue identified during the modelling process is how to guarantee the accuracy of all the components, including the connections between different surfaces, the precise curvature of the shapes, the correct dimensions of the components which may partly omitted in the rulebook. To solve these issues, several experiments were undertaken. To merge the surface connections together and prepare for the later printing process, inspections are made both automatically and manually. The problem surfaces can usually be found using automatic inspections. The gaps on the outer surfaces are also normally easy to find, although some small gaps might be ignored, such as the example in Figure 184. However, the overlapping of surfaces inside a volume is difficult to detect. If this occurred, the target component must be “opened” and problem areas must be fixed manually, such as the example shown in Figure 185. But in general, since the software used (i.e. Rhino/Grasshopper) is parametrically based, the manual fix work is only done when necessary, in a rate of about less than ten problem areas out of thousands of surfaces. Therefore, the overall process is still much advanced than the traditional way of checking the carpentry work surface by surface solely by the carpenter. Regarding the precise curvature of the shapes, there are mainly two different types. The curvature of the *dou* at the lower part of the block is a real curve (see Figure 186) where the curvature is based on other dimensions of the block. But the “curvature” of the *gong* at the both ends (see Figure 187) is made using several straight lines rather than a real curve. Apart from these, some omitted details or unclear descriptions also occurred in the rulebook which brings difficulties in the modelling process. An essential way of solving this is to confirm the information of all the related nearby components and then derive the absent information then get a reasonable assumption. After this, the component is placed back into the whole model and check whether it is consistent with the nearby components or not. Several components such as the hollow parts of *ang*, the slope of *li shua tou* and *wai shua tou*, the middle supportive part of *hua tou zi* are carried out by this method (see Figure 188).

Here, different colours are used in the digital models only to identify different elements since several of them are very similar in shape and in turn it is easy to get confused. The colours here do not contain other meanings. In practical cases there is no colour difference for all the elements.

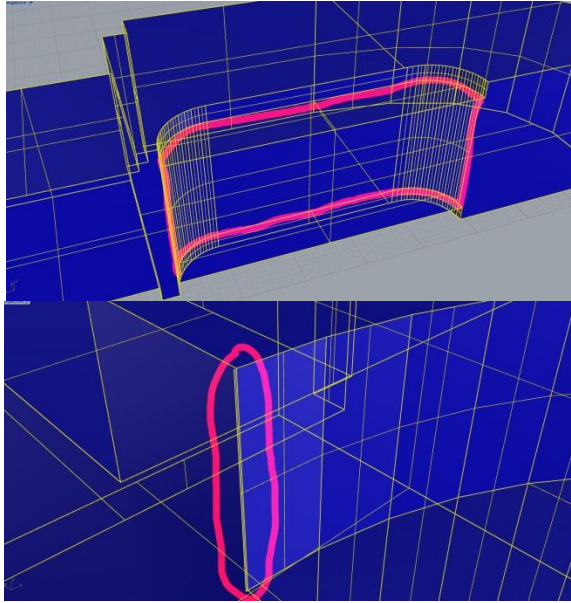


Figure 184. Problem surface (left) and its small gap on the outer surface

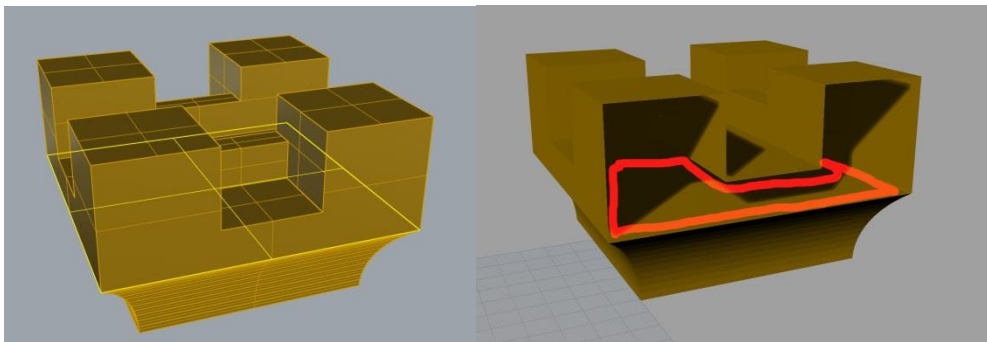


Figure 185. The overlapping of surfaces inside a volume

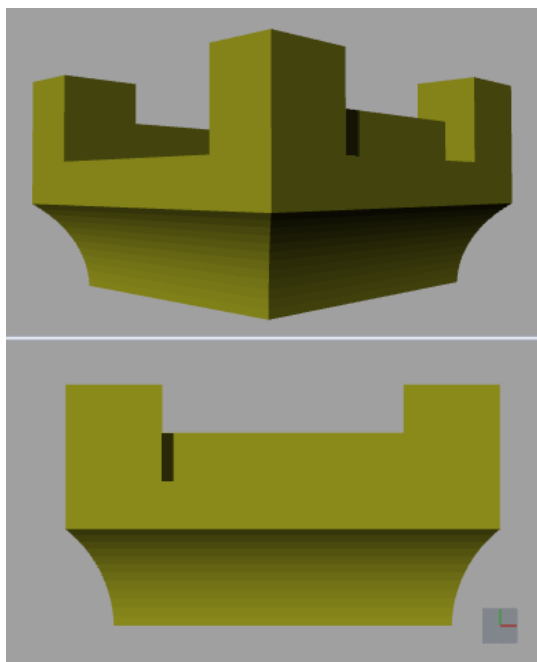


Figure 186. The curvature of the *dou* at the lower part of the block

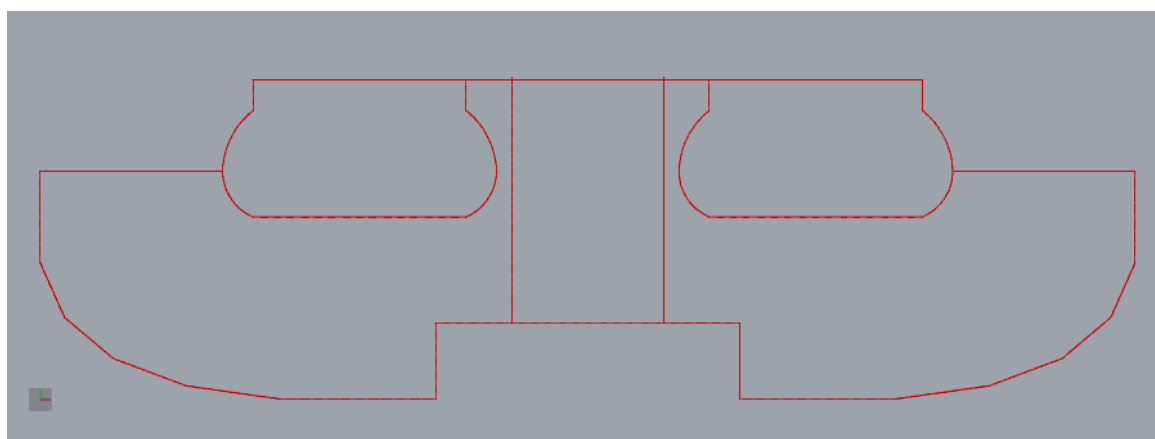


Figure 187. The “curvature” of the *gong* at the both ends

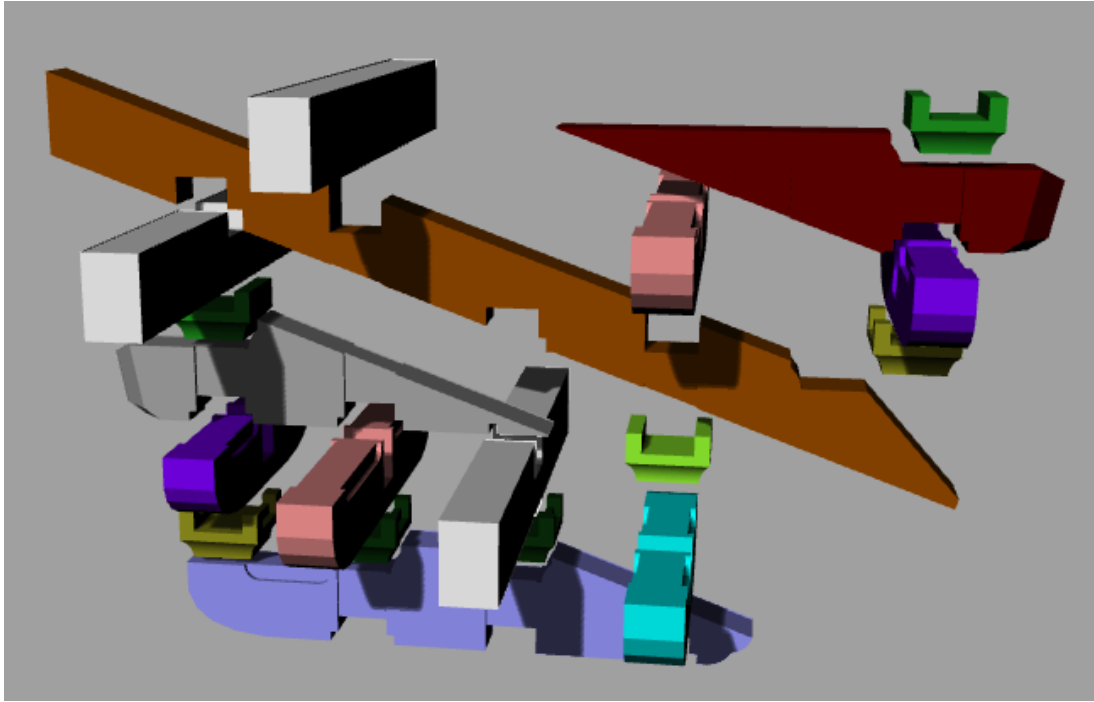


Figure 188. Assumption and checking process for the hollow parts of *ang*, the slope of *li shua tou* and *wai shua tou*, the middle supportive part of *hua tou zi*

From the above evaluation, a set of revised version of the fifteen components are digitally produced, as shown in Figure 189.

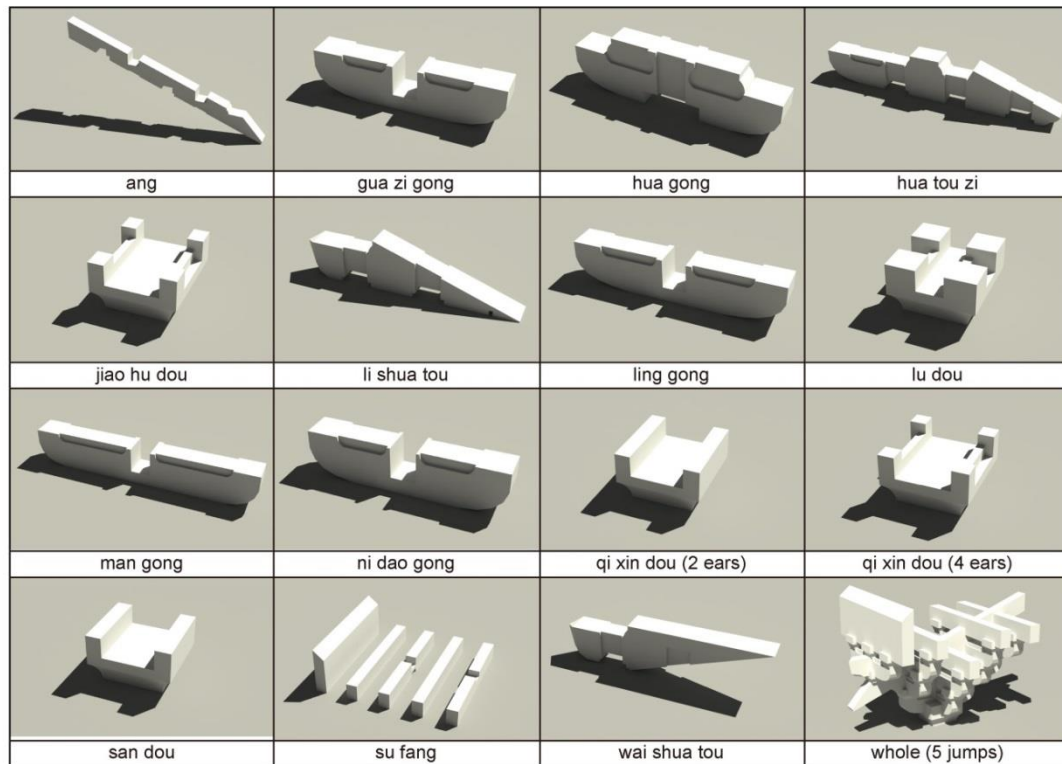


Figure 189. The digitally represented components of the *dou gong*

5.3.2 The digital fabrication of the paper components

Conventional fabrication of the joint would be in wood. In digital fabrication, many options are open to us such as powder, wax, plastic, metal and, less common, paper. In this research, a relatively recent 3D digital fabrication technique using built up sheets of paper (see Figure 190), which is “3D Printer Matrix 300+” (see Figure 191), is selected for the following reasons. Paper, compared with plastic, is a sustainable material which does not pollute the environment and when laminated together in multiple layers, it becomes very strong and rigid compared to powder and wax. At the same time, compared with metal, the micro space between sheets can be compressed when needed, which maintains the elastic character of the traditional wood material and also the function of the joint. And this feature gives advantage when assembling the components: even without pre-defining the tolerance, different components can insert into each other tightly but without damaging the contact surfaces. This advantage is also discussed later in the tolerance discussion. In addition, the character of the laminated layers of the paper has similarity with the glulam wood material, which brings a future research option on the material choice of the joint. For comparison, a powder model version is used as a comparison (see Figure 192) but showed that it is less appropriate than the one made using paper because the powder components were relatively weak and fragile and therefore not

suitable for assembly and re-assembly. Also, the power joint does not maintain the elastic character as paper or wood.

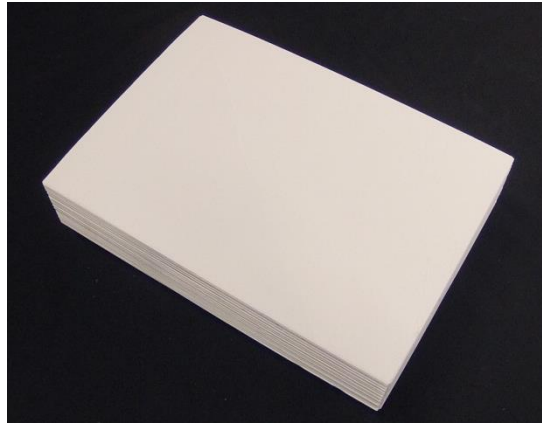


Figure 190. Digital fabrication material: paper



Figure 191. 3D Printer Matrix 300+ (Mcor Technologies Ltd, 2015)

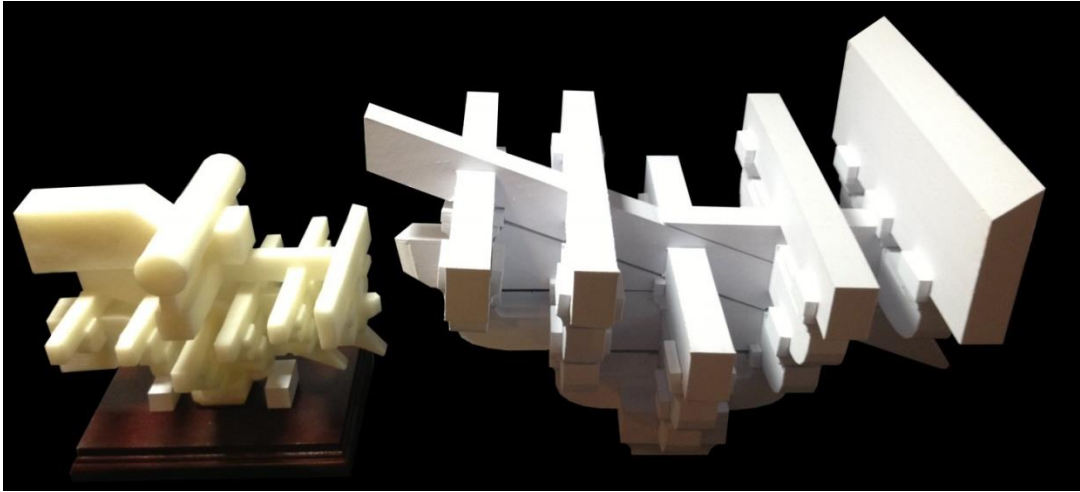


Figure 192. A powder model version (left) is used as a comparison of the paper model (right)

In order to make full use of the 3D printer and produce the components effectively, all the 43 pieces of the fifteen elements (due to the repetition of some elements) digital models are carefully organized according to the geometrical shapes (see Figure 193) so that they can be composed within one stack of paper which is the raw material that the MC or 3D printer uses (see Figure 194). Consequently the joint components could be completed in one printing.

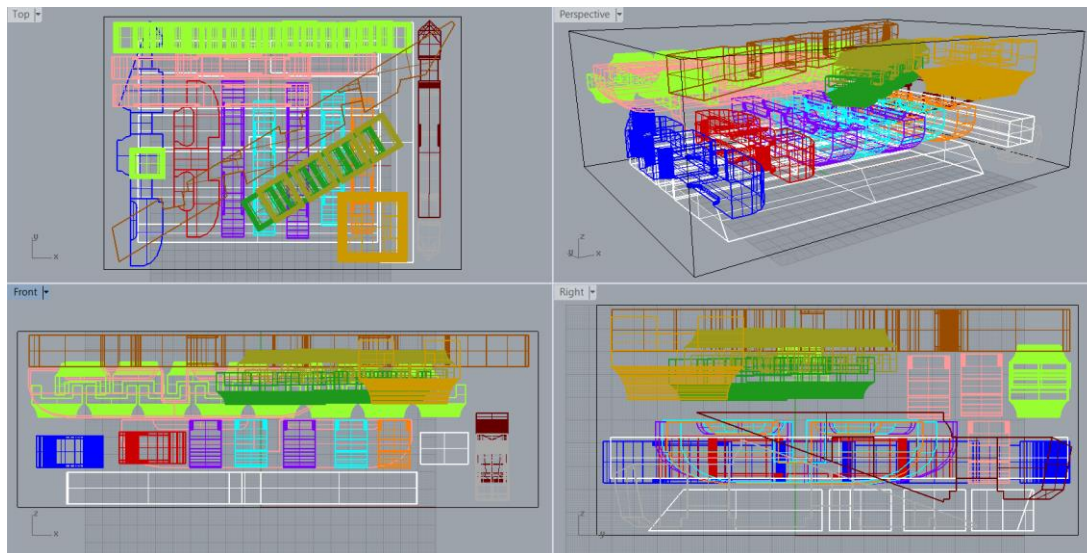


Figure 193. Arrangement of 43 pieces of the fifteen elements according to the geometrical shapes

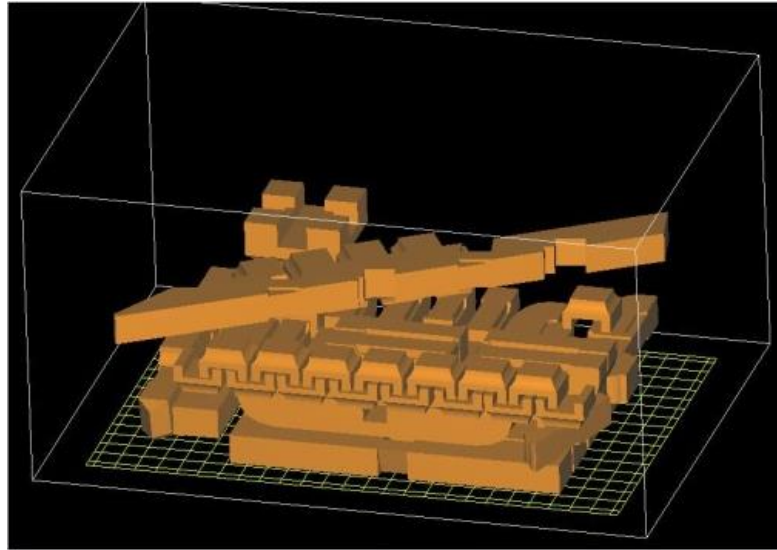


Figure 194. The components are composed in the digital model to allow fabrication from a single block

5.3.3 Practical problems and modifications

During the process of extracting the components from the paper block and peeling off the spare material (see Figure 195), practical problems arose with the *jiao hu dou*, *qi xin dou* (two ears), *qi xin dou* (four ears) and *san dou* constructions. In the paper stack, in order to save space to a maximum level, these small scale *dou* are arranged in a position such that they partially interlock (see Figure 196). However in practice it proved very difficult to extract each individual component without damaging the faces of an adjacent component.

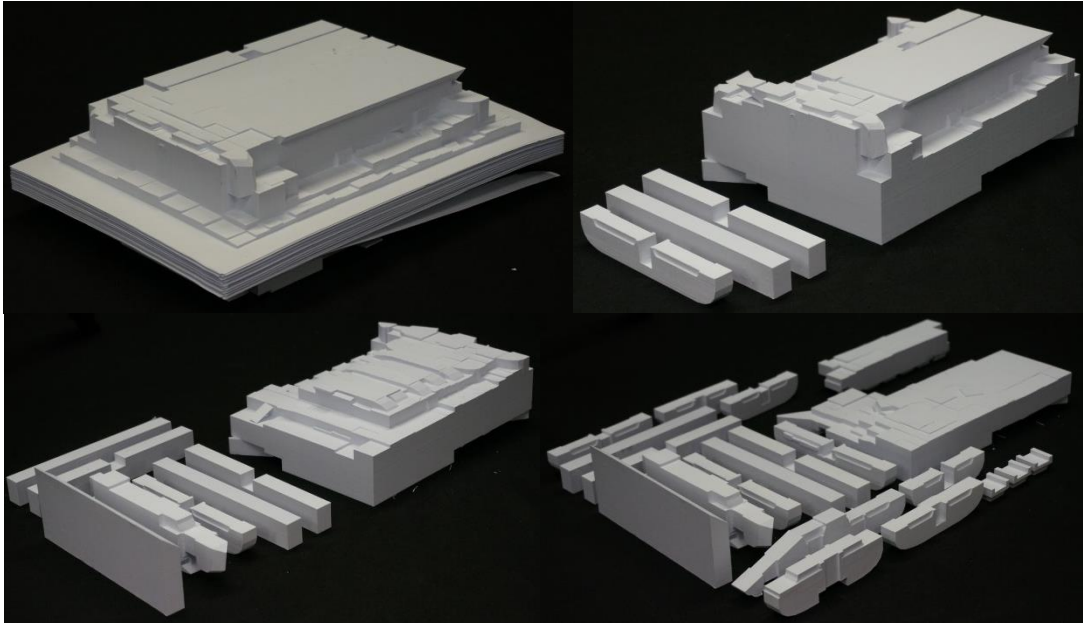


Figure 195. Extracting process of the components from the paper block

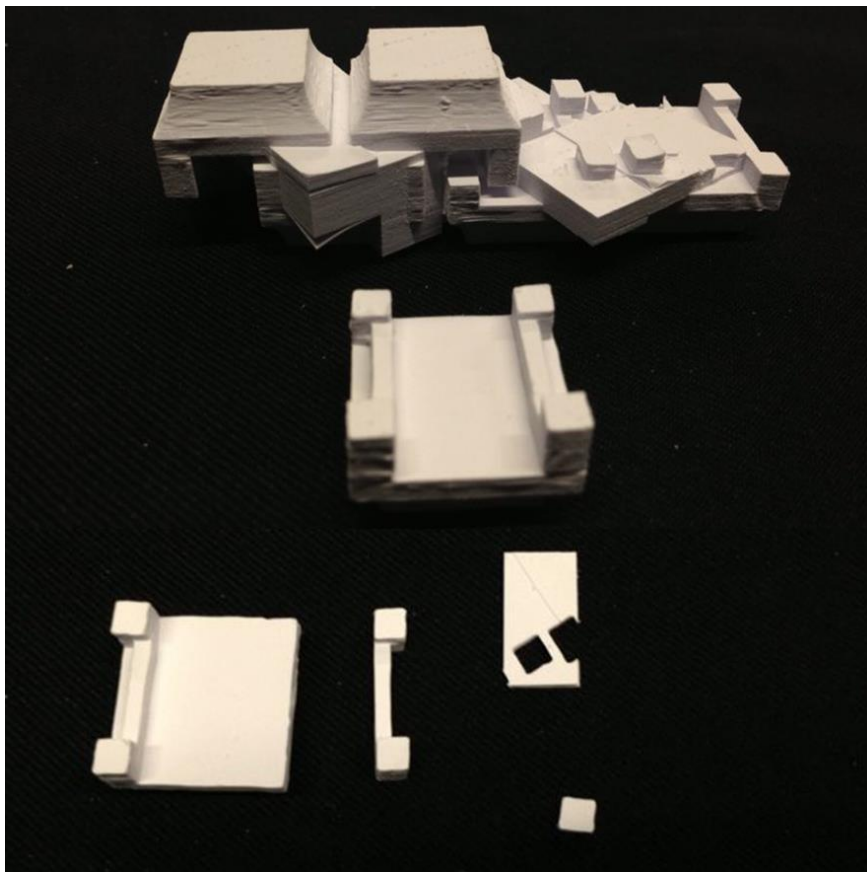


Figure 196. Practical problem happened in digital fabrication process

Modifications are made to these five elements in fabrication process. They are arranged as a single layer without overlap (see Figure 197). With this arrangement, the small delicate parts could be extracted without damage, as shown in Figure 198. This is also the quickest way to reproduce these pieces considering the paper 3D printer makes the fabrication layer by layer (sheet by sheet). And indeed, this single layer models could also be properly arranged into the previous composed models of one paper stack and be printed once. After this, all the elements will be peeled off and assembled to complete the *dou gong*. Figure 199 shows all the final physical models of components and the assembly process of the physical models will be described in the next section.

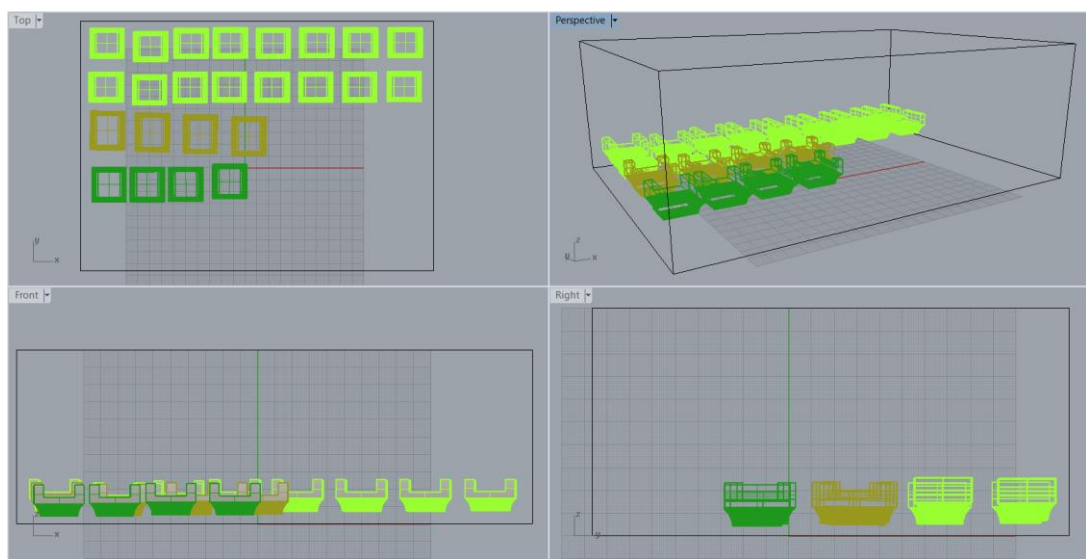


Figure 197. Modification of the arrangement

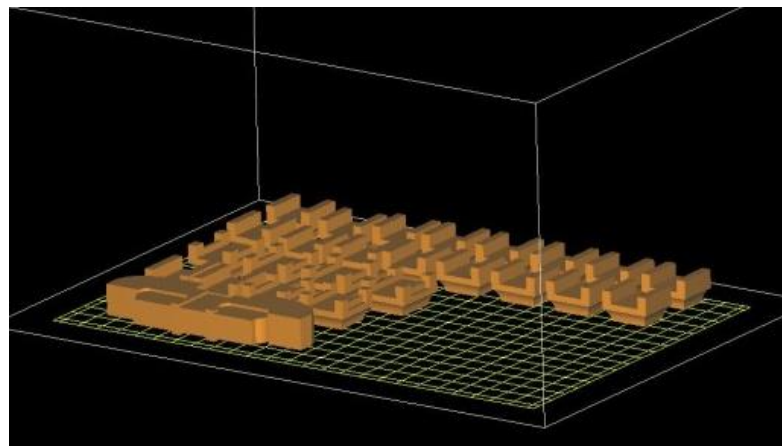


Figure 198. Single layer arrangement for printing

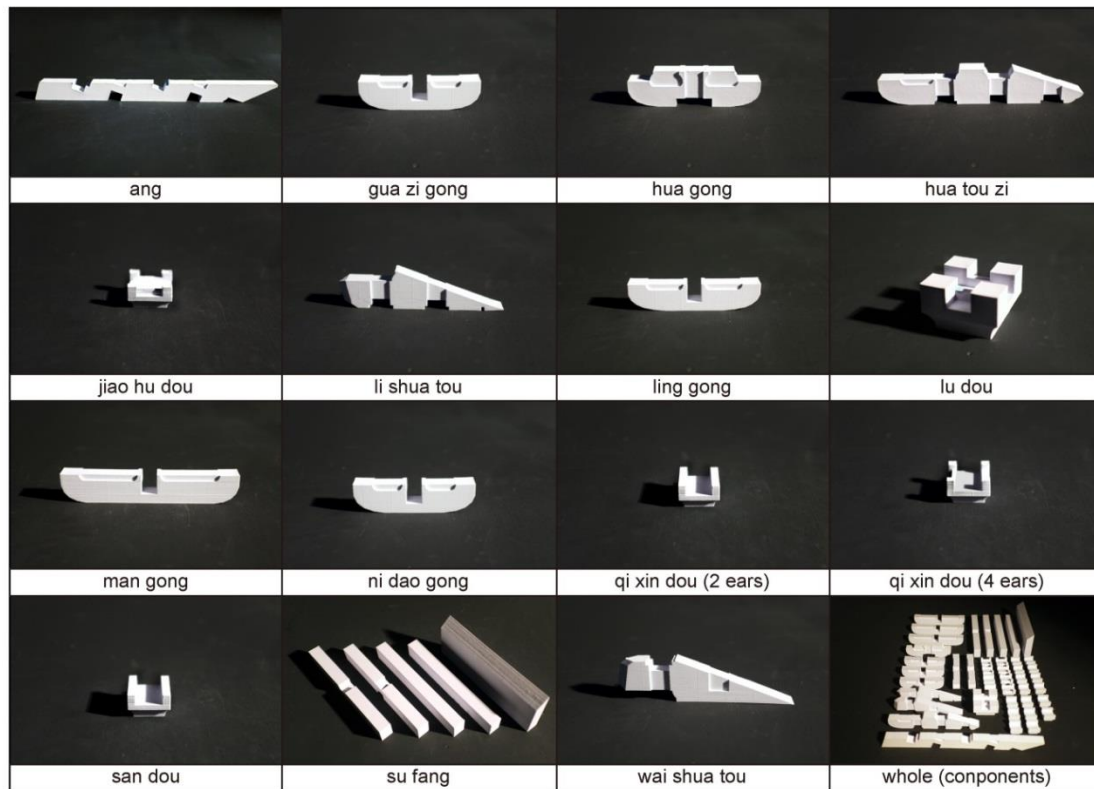


Figure 199. The digitally fabricated paper components

5.3.4 Assembly of the fabricated components

When all the physical components are ready, they will be assembled into a complete joint in a defined order. To make this process more efficient and accurate, a digital simulation of the assembly orders is established prior to the physical assembly, as shown in Figure 200. The assembly process consists of 18 steps. In each step, the component(s) marked in red is the newly-added one. Following this, the physical assembly is carried out correspondingly, as shown in Figure 201. Consequently, a complete joint model is finished. Figure 202 shows the view from different angles to the joint model.

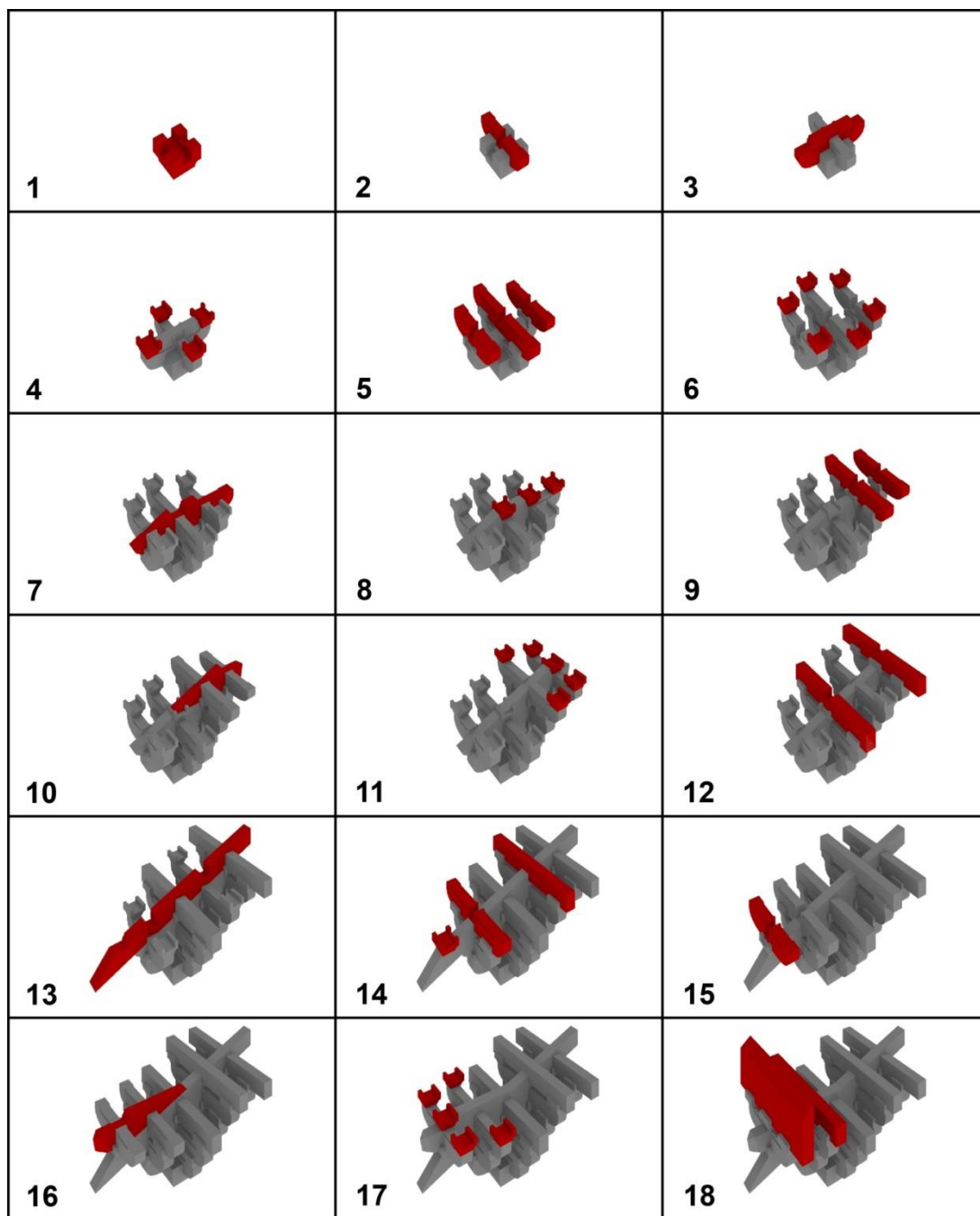


Figure 200. Digital simulation of the assembly orders



Figure 201. Assembly of the fabricated components into a complete joint

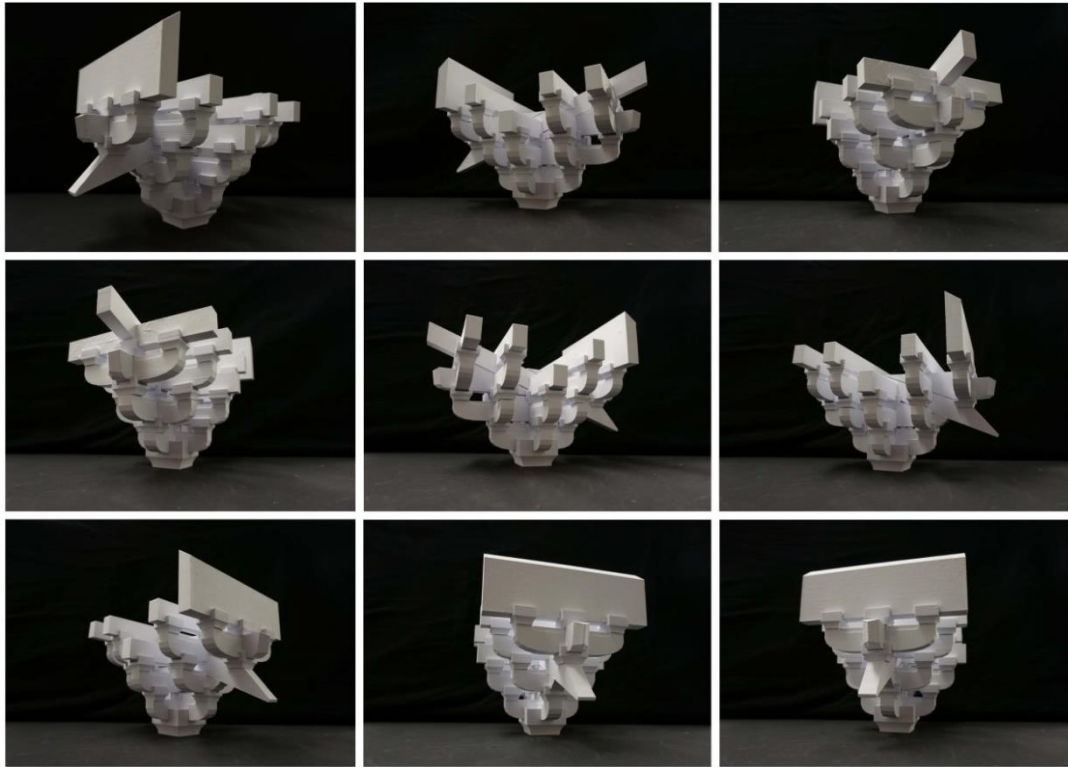


Figure 202. View from different angles to the joint model

5.3.5 Discussion

After assembly, because the construction is extremely closely fitting, an analysis of the degree of error in the fabrication process is made by accurately measuring the dimensions in-plane and across-plane using a digital calliper (see Figure 203), to ensure that it is within an acceptable level. An example is shown in Figure 204, all the dimensions including the outer length, inner cut length and detailed part length are measured. To reduce the human error in this process, each data is measured a few times and the average value is recorded in the summary table. After measuring all the fifteen elements, the typical results are documented in the table with the calculation of the tolerance, as shown in Figure 205. The tolerances are established by comparing the actual size of the physical models versus their digital dimensions. The majority of the tolerances measured proved to be good and the average tolerance was 0.94%, which is acceptable.

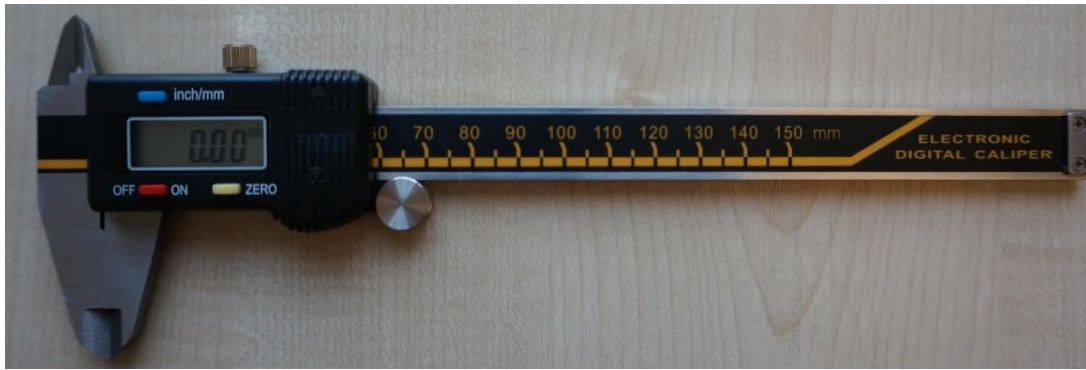


Figure 203. Digital calliper

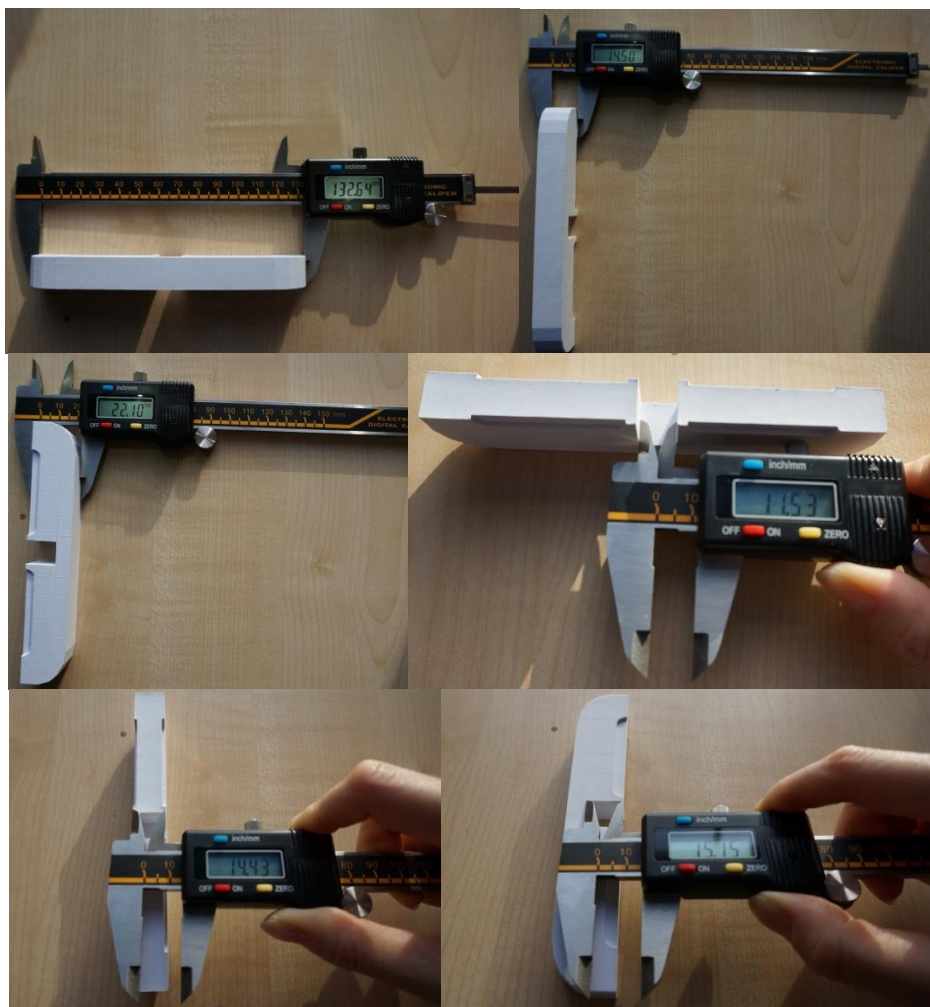


Figure 204. An example of the measurement to one component

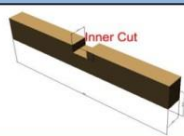
Table Name					
Model Image	Toponym		Digital Model (mm)	Physical Model (mm)	Tolerance (%)
su fang					
	Length		159,51	159,38	0,08%
	Width		14,4	14,77	2,57%
	Height		21,6	21,63	0,14%
	Inner Cut length		14,4	14,36	0,28%
	Inner Cut Width		14,4	14,68	1,94%
	Inner Cut Height		7,2	7,26	0,83%
ni dao gong					
	Length		132,48	132,64	0,12%
	Width		14,4	14,36	0,28%
	Height		21,6	21,72	0,56%
	Inner Cut length		11,52	11,53	0,09%
	Inner Cut Width		14,4	14,43	0,21%
	Inner Cut Height		14,4	14,25	1,04%
lu dou					
	Whole	Length	46,08	46,11	0,07%
		Width	46,08	46,13	0,11%
		Height	28,8	29,5	2,43%
	Inner Cut 1	Depth	46,08	46,2	0,26%
		Width	14,4	14,39	0,07%
		Height	11,52	11,81	2,52%
	Inner Cut 2	Depth	15,84	15,85	0,06%
		Width	14,4	14,35	0,35%
		Height	11,52	11,71	1,65%
	Ear	Length	15,84	15,71	0,82%
		Width	15,84	15,94	0,63%
		Height	11,52	11,81	2,52%
	Bao er	Length	14,4	14,71	2,15%
		Width	4,32	4,33	0,23%
		Height	5,76	5,87	1,91%
ang					
	Whole	Length1	264,81	264,9	0,03%
		Length2	2,38	2,41	1,26%
		Length3	38,39	38,37	0,05%
		Length4	238,91	238,89	0,01%
		Length5	22,97	22,97	0,00%
		Width	14,4	14,66	1,81%
		Depth	22,97	22,97	0,00%
	Inner Cut 1	Width1	14,4	14,29	0,76%
		Width2	4,32	4,27	1,16%
		Height1	7,63	7,53	1,31%
		Height2	8,65	8,49	1,85%
		Height3	5,75	5,68	1,22%
		Depth	14,4	14,31	0,62%
		Inner Cut 2	Width	14,4	14,13
	Height1		14,13	14,01	0,85%
	Height2		8,92	8,73	2,13%
	Inner Cut 3	Depth	14,4	14,35	0,35%
		Width	14,4	14,26	0,97%
		Height	5,41	5,47	1,11%
	Inner Cut 4	Depth	1,44	1,42	1,39%
		Width1	14,4	14,24	1,11%
		Width2	2,16	2,13	1,39%
		Height1	5,04	4,98	1,19%
		Height2	7,93	7,9	0,38%
	Inner Cut 5	Height3	3,88	3,85	0,77%
		Depth	14,4	14,64	1,67%
		Width	14,4	14,32	0,56%
		Height1	13,12	12,9	1,68%
		Height2	7,9	7,87	0,38%
	Average tolerance				

Figure 205. Tolerances: established by comparing the actual size versus the digital dimension

Improper storage may cause the damage of the physical model, such as it may break into parts (see Figure 206). Also, the delicate parts, such as the ears of the *dou* may be broken from the laminated layers (see Figure 207). The possible solutions to such problem can be to glue back the broken laminated layers, or, simply take another block of laminated layers and make up the broken part, as shown in Figure 208. Then

the repaired structure can be put back (see Figure 209) and re-assembly (see Figure 210). Due to the elastic and rigid characters of the paper material, the repair and re-assembly process is possible.

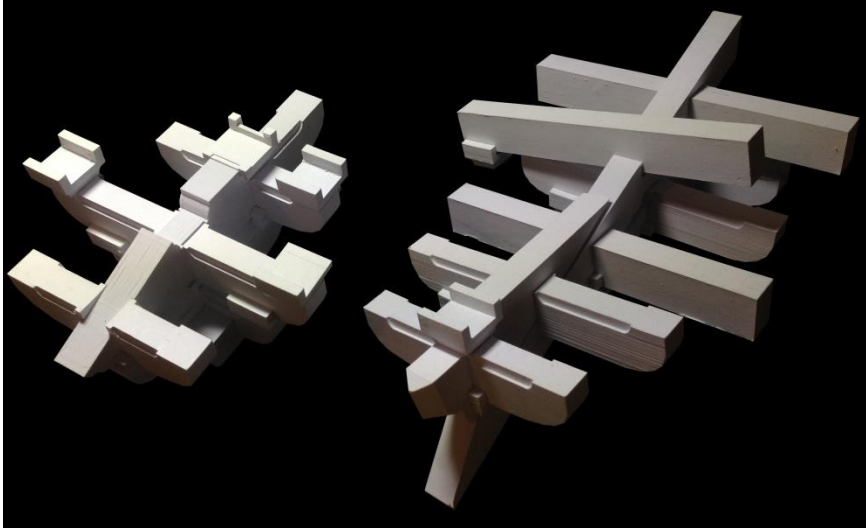


Figure 206. Break into parts

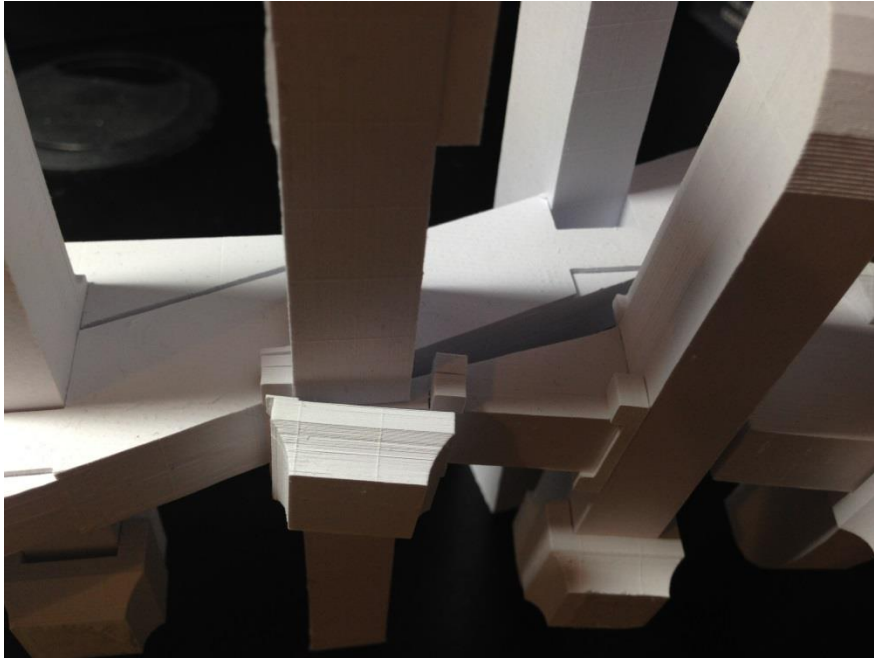


Figure 207. Damage of the *dou*

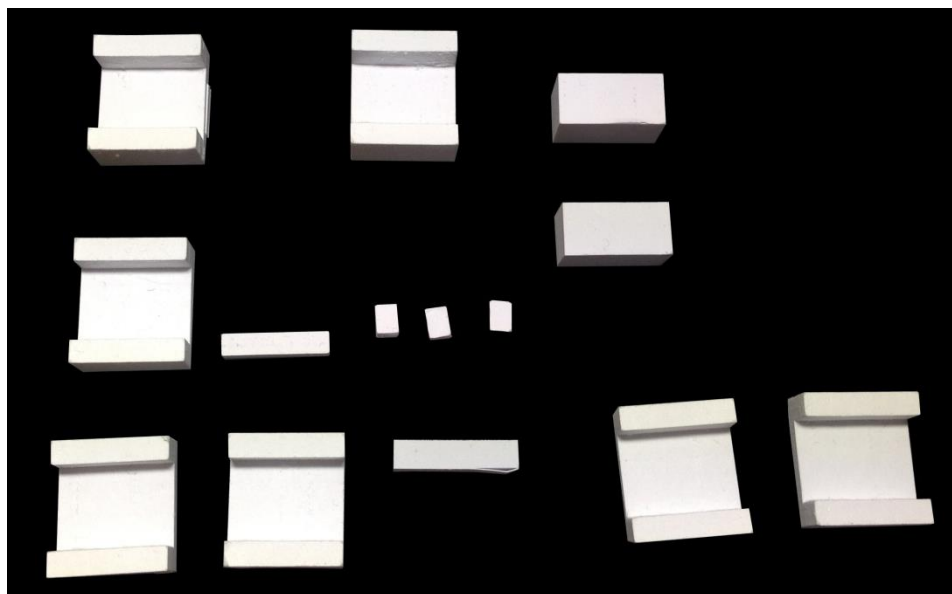


Figure 208. Repair of the *dou*



Figure 209. Repaired ear of the *dou*

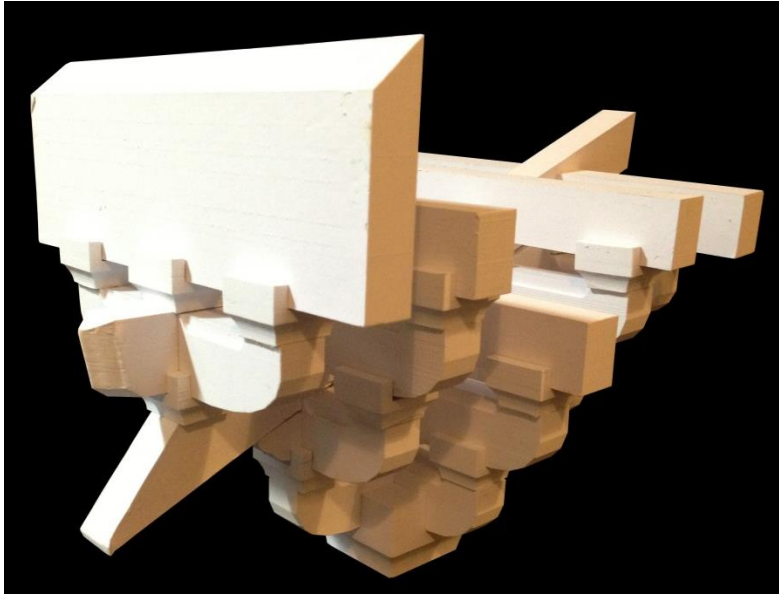
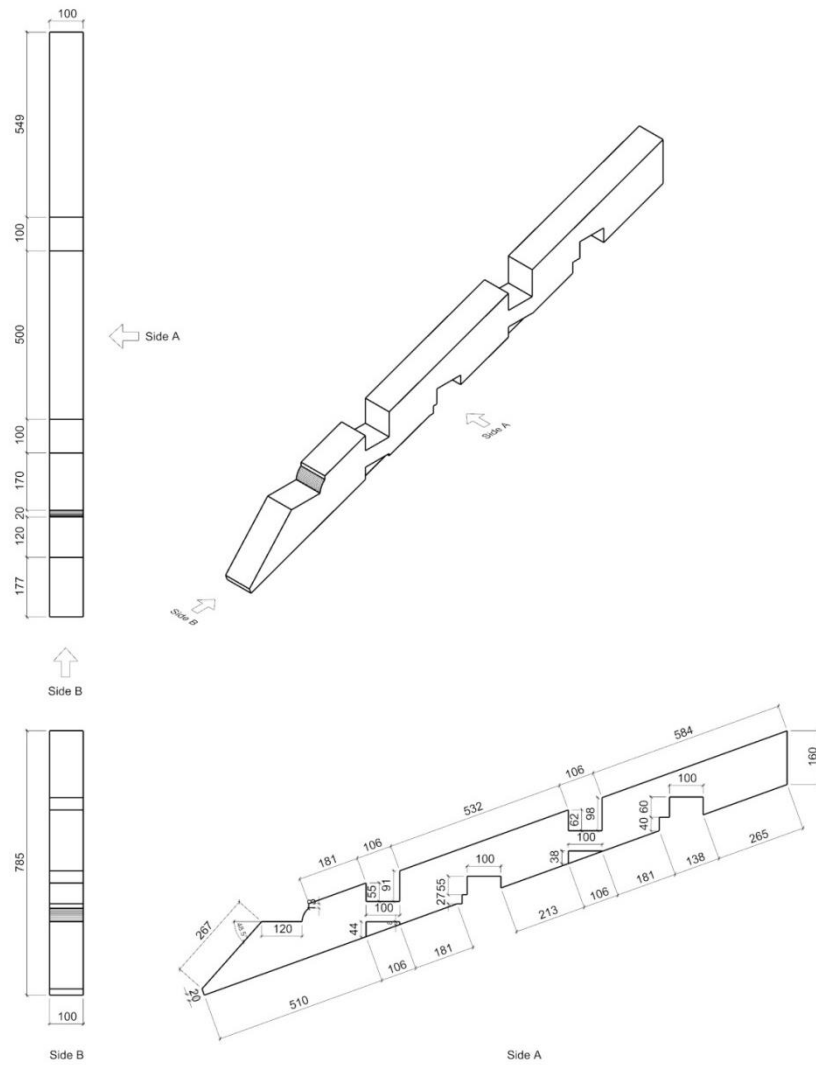


Figure 210. Re-assembly of the joint

5.4 Summarized information for parametric modelling

By completing the digital fabrication approach to *dou gong*, we have prepared a solid foundation for the parametric interpretation of *dou gong* by clearly understanding the inter-relationships of the individual elements, including those omitted from the rulebooks and those remained unclear in historical references. When summarizing all the data obtained from the digital fabrication process, a set of very detailed drawings of the fifteen key elements of *dou gong* will be given with the core information needed in parametric modelling. In this set of drawings, we set 1 *dou kou* = 10 *fen* = 100 as the measurement illustration. So in the next stage, the algorithm consideration will be based on the “multiple times” relationships between different elements rather than the absolute values. The accuracy of this set of drawings lies on both the *Ying Zao Fa Shi* information and Liang’s analysis to it, as well as the experimental outcomes from the digital fabrication process. Thus, the examples from extant buildings or those undiscovered heritages may be slightly different from the data here. But if any data requires update in the future, the parametric algorithm can be updated by changing the value of the “multiple times” relationship easily.

ang

Figure 211. *Ang*

gua zi gong

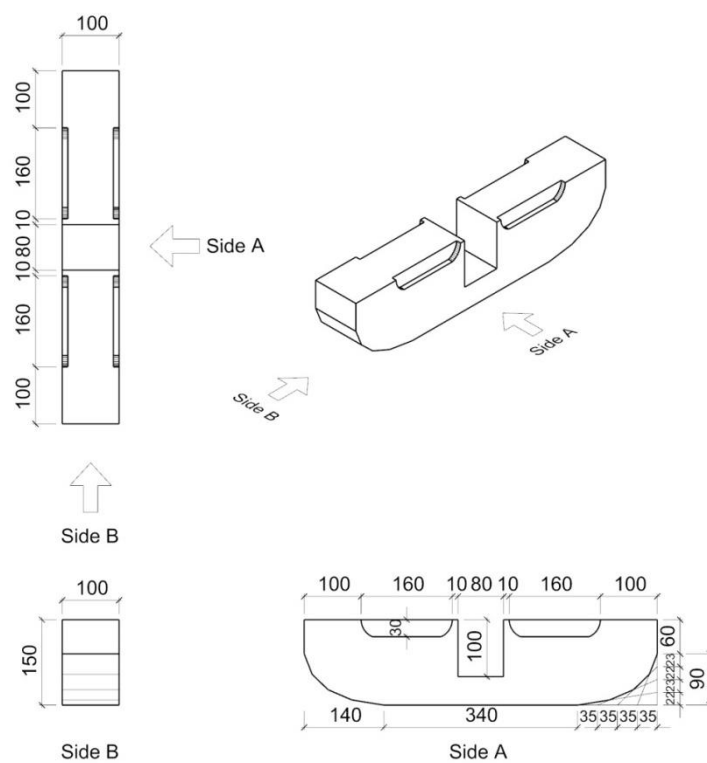
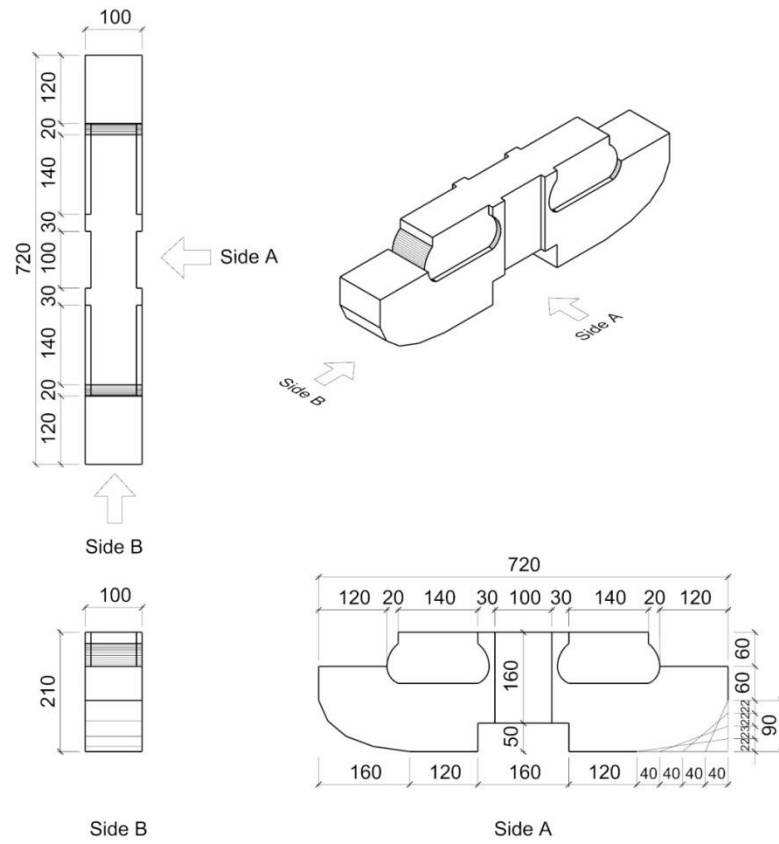


Figure 212. *Gua zi gong*

hua gong

Figure 213. *Hua gong*

hua tou zi

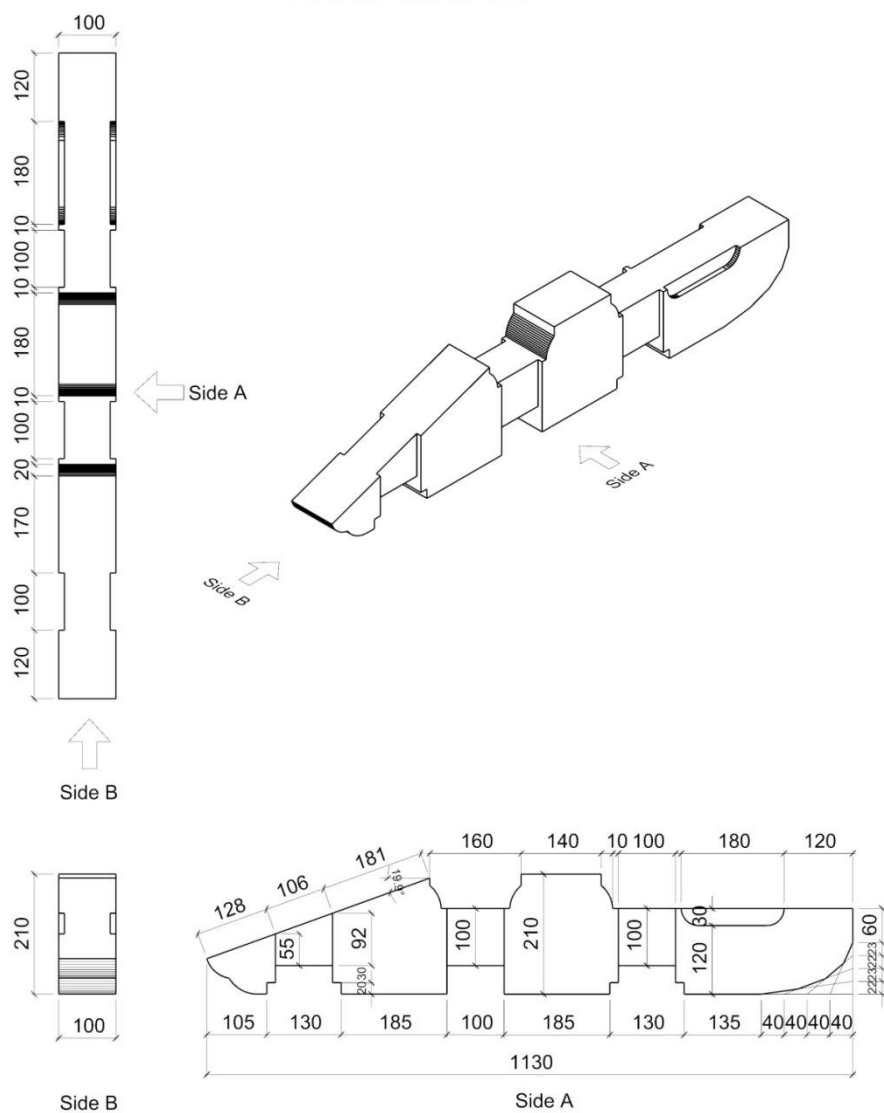
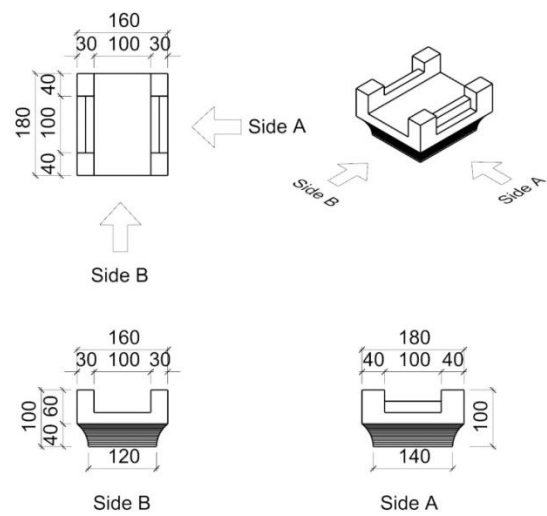


Figure 214. *Hua tou zi*

jiao hu dou

Figure 215. *Jiao hu dou*

li shua tou

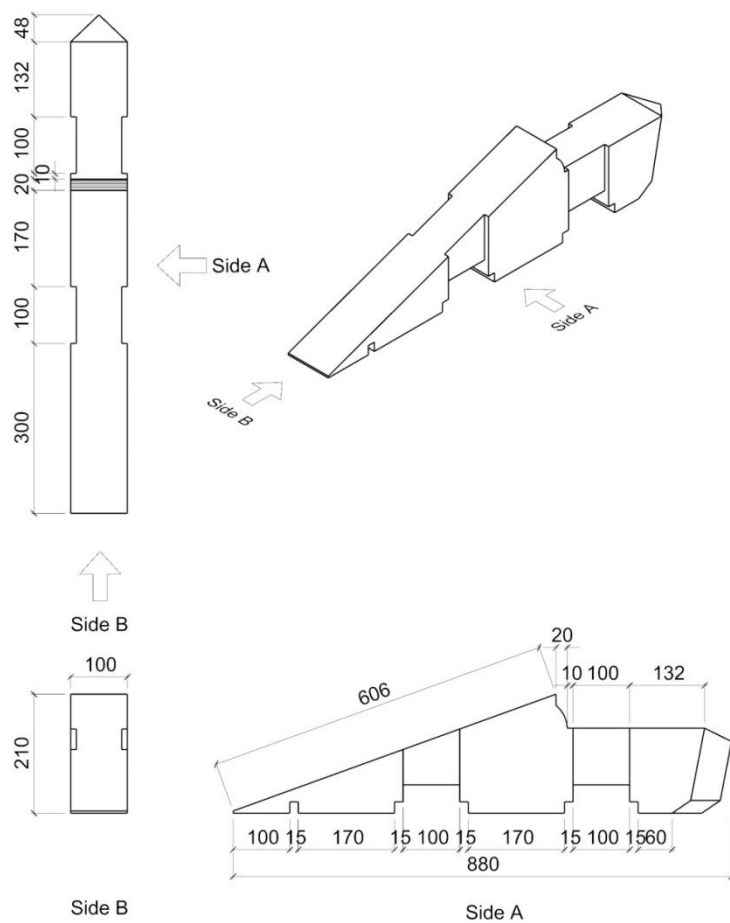
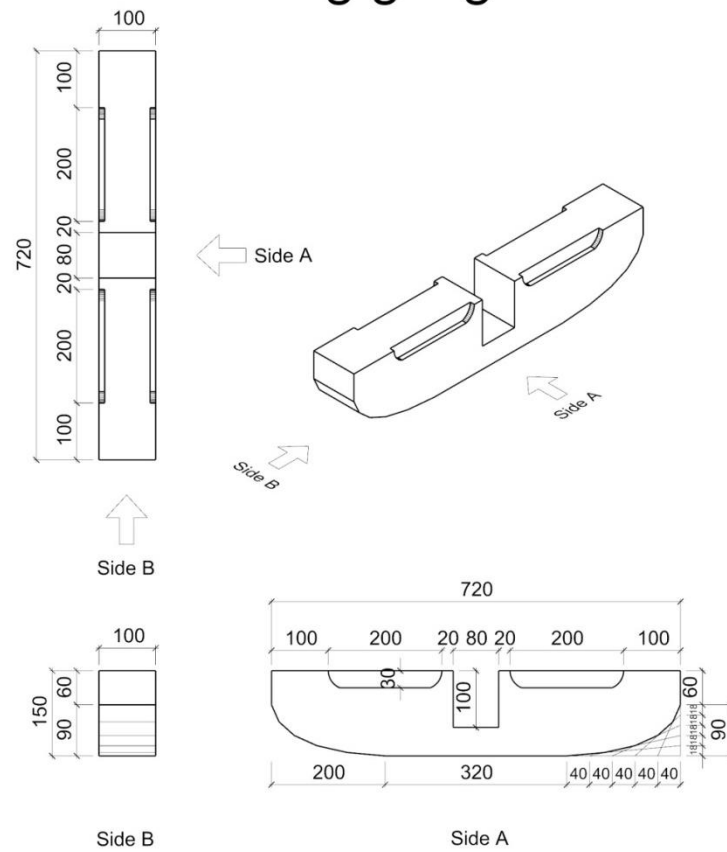


Figure 216. *Li shua tou*

ling gong

Figure 217. *Ling gong*

lu dou

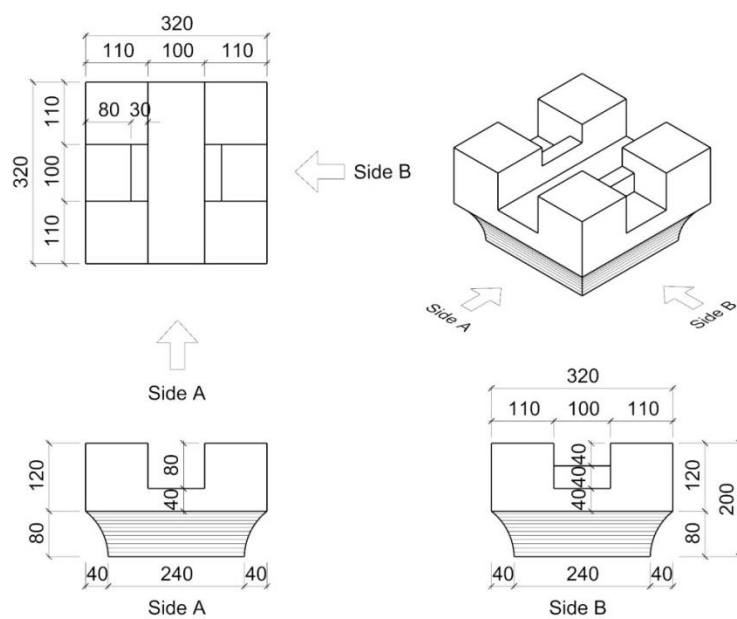


Figure 218. *Lu dou*



Figure 219. *Man gong*

qi xin dou (2 ears)

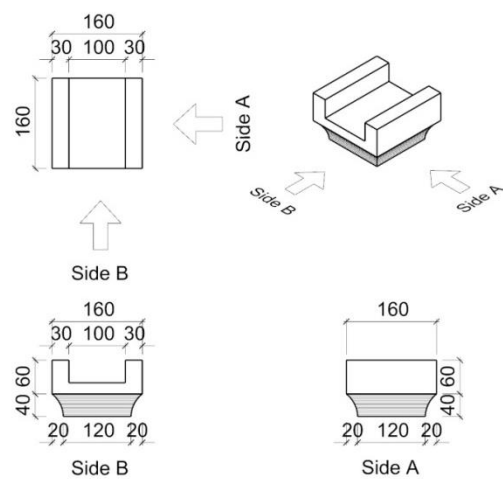


Figure 221. *Qin xin dou* (2 ears)

qi xin dou (4 ears)

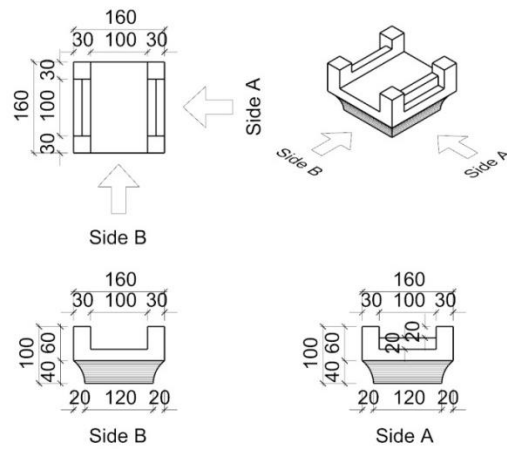


Figure 222. *Qi xin dou (4 ears)*

san dou

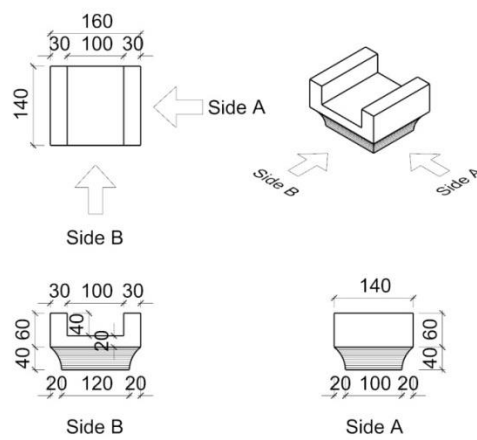


Figure 223. *San dou*

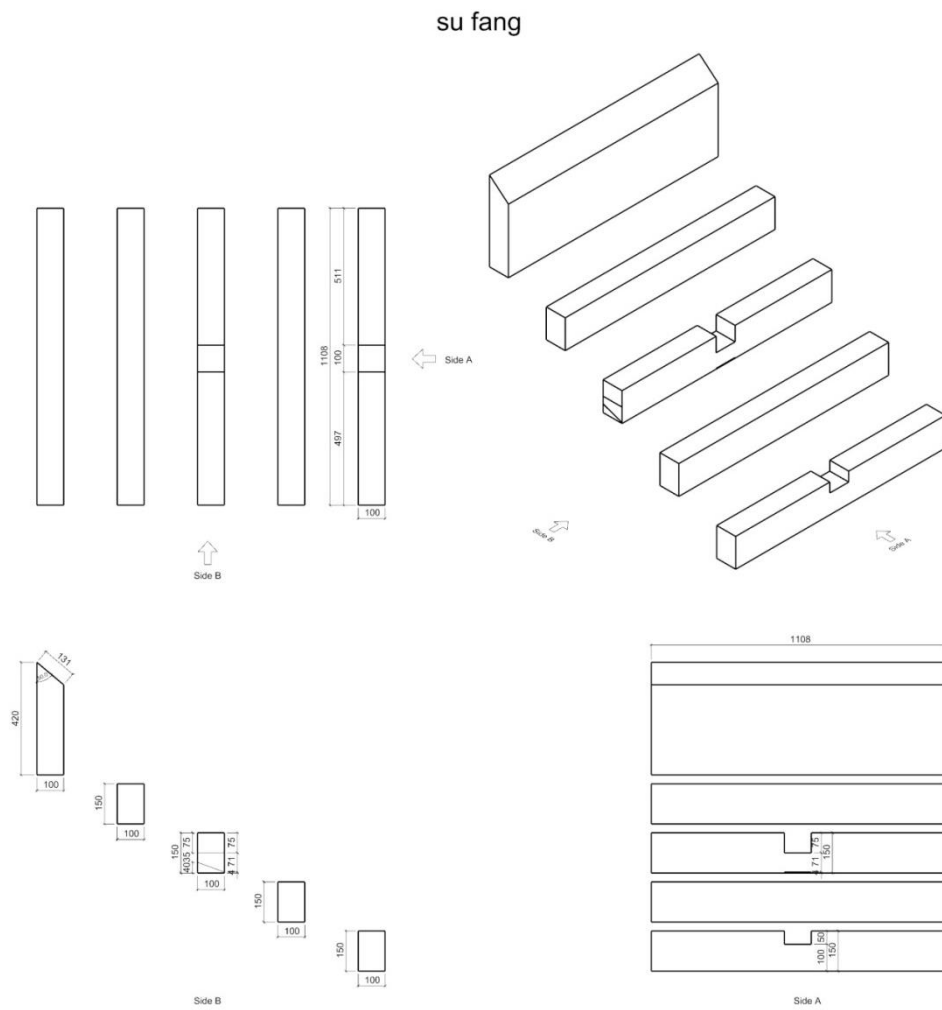


Figure 224. *Su fang*

wai shua tou

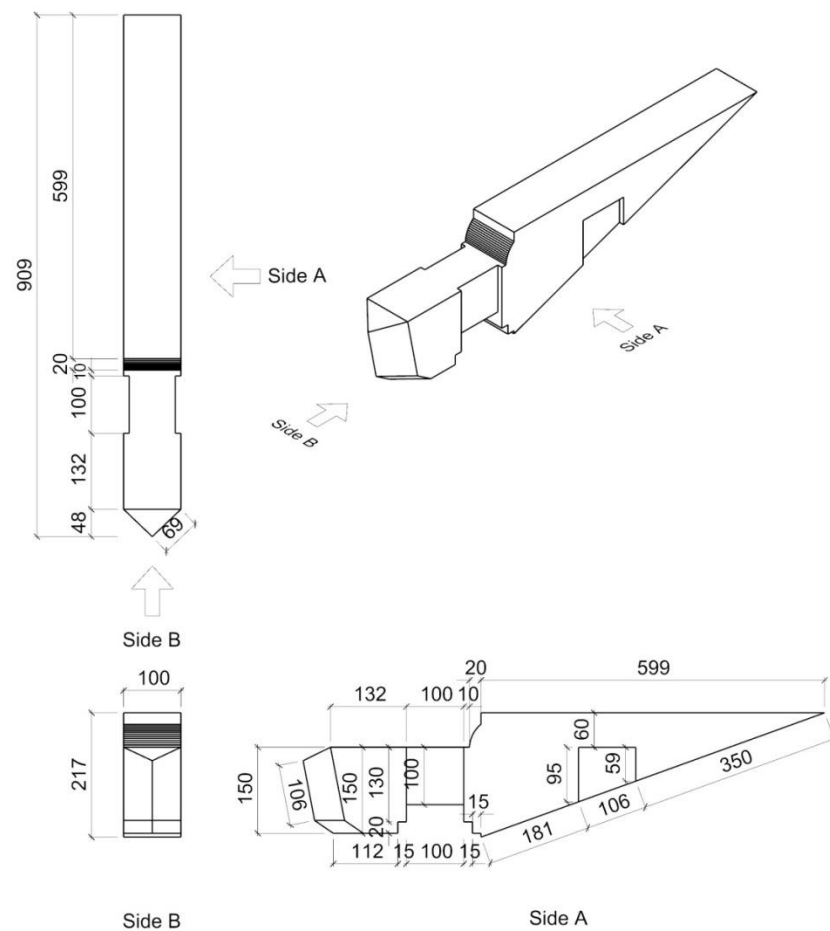


Figure 225. *Wai shua tou*

5.5 Bottom- Up method in parametrics

After the digital fabrication process, the ambiguities have been largely clarified. Especially, when referring to the set of the summarized drawings, the algorithm can be derived and then the elements can be parametrically represented. However, due to the extreme complexity of the joint, there will be different ways to interpret it and approach it. In turn, the outcomes could be unpredictable. Also due to the amount of work needed, it is not feasible to complete all the elements parametrically one by one in each attempt. Therefore, the focus will be the process itself and how to establish the algorithm and in turn to present the parametric model, rather than making a model that only for visualization in a CAAD software. Although this process is a complex act of thinking and will be a long way to go, the benefit is that parametric design and its requisite modes of thought will largely extend our understanding to the

complex structure and finally achieve the intellectual scope of design in reviving the traditional styles.

5.5.1 Attempt 1

In the first attempt, the focus of the tests is to parametrically present the *dou* and study on how the parameters and algorithm could be controlled. Since the several types of *dou* are similar in shape and characters, the base block *lu dou* is selected as the test target. As discussed before, the rulebooks are not written in parametric language aiming for the algorithmic representation, but they give guidelines, descriptions and drawings. So such information can be set as the core, or the modelling goal. Then we need to find out the available parametric techniques as a strategy to fulfil the core. This is the “outcome centred” process, which requires a large amount of work in technique choice. But once this is successfully achieved, the aim of that “parametrics serve the style” is carried out.

In the initial test, since we already get all the dimensions of *lu dou* in the last section, the most original way is taken: based on the dimensions, all the points on *lu dou* surface can be confirmed. To set up these points, the index labelling and list are used. Then all the points are connected according to the certain orders to make the lines, and in turn the surfaces, and finally the block volume (see Figure 226). The modelling process is shown in Figure 227. This method is quite straight forward in getting the algorithm and the model. But the disadvantage is also obvious. First, it requires a huge amount of the algorithm in presenting the points on the surfaces. In the test, only one element is presented but the list of the points is very long. As a result, when connecting the points to form up the lines and surfaces, chaos may happen in choosing the connection orders or the correct the points. Consequently, if this method is continued, we can predict that in principle the rest of the elements can be modelled but this is neither an efficient nor a sensible way. Second, even if all the elements are presented in this way, the relationship between different elements highly relies on the relationship of the points on different elements. But according to the digital fabrication process, it is believed that the contacted surfaces are the linkage closely link up different elements. Therefore, if we would like to build up the relationship based on the surface and control the surface adequately, we have to manage the points in groups in a way that they form controllable surfaces. This requires extra relationships to be built up and will increase the complexity in the algorithm. Therefore, this test is terminated here although the prediction is that the joint can be modelled in this way. We then need an optimization to focus on the surface and the volume, as well as the relationship with the nearby surfaces. In other words, we need a controllable and flexible algorithm to present the elements.

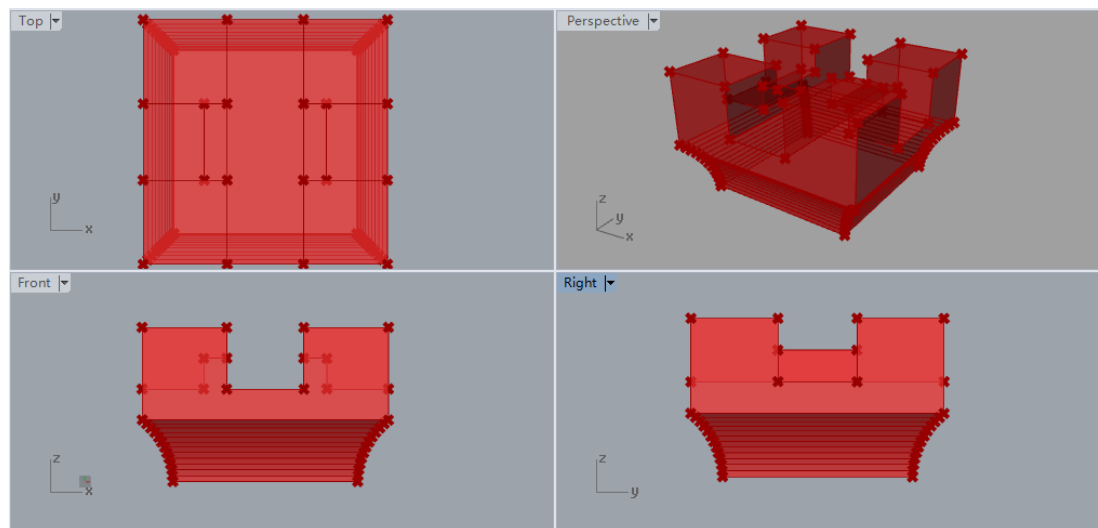
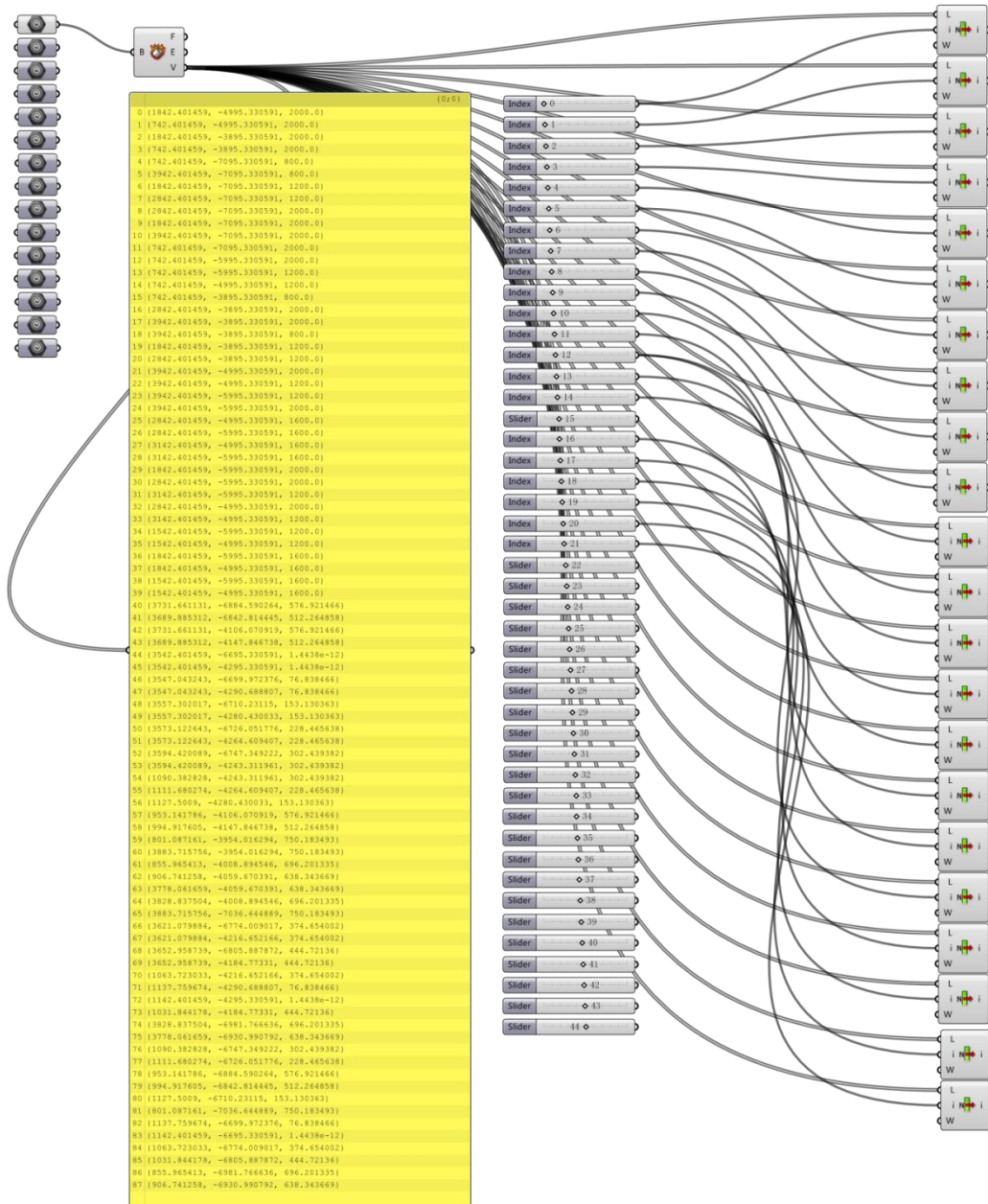


Figure 226. Initial test of *lu dou*

Figure 227. Modelling process of the initial test of *lu dou*

To optimize the algorithm, the focus is shifted to the surfaces rather than the points. As shown in Figure 229, the modelling process can be managed in two groups: the upper part with mainly rectangular surfaces and the lower part with an arch curve. To build up the upper part, the length of the height, width and depth of each rectangle are all linked together. And all the rectangles are linked to the base rectangle. The base rectangle is defined by the basic length of *dou kou*. Therefore, in deed all the parameters are ultimately linked to the basic length of *dou kou*. This is the basis in order to include the *Cai* concept in the future modelling work. In the modelling of

the lower part, the arch curve is controlled by an arch function, which is also adjustable. Thus, the complete *lu dou* is established with the optimized algorithm, as illustrated in Figure 228. In this test, although the algorithm seems requires similar workload as the previous one, it is indeed a clearer and more intelligent logic. The surfaces are closely linked together within this element. And meanwhile, they are controllable when later other contacted elements are added in. In addition, since all the parameters and surface relationships are ultimately linked to the basic length *dou kou*, when including other elements, all the parameters of other elements will also be consistent with the current relationships. This is a sufficient evidence that by continuing this method, the complete joint could be parametrically presented. Figure 230 shows the variations of this test. Although not all the variations would appear in practical cases, it shows a good control and flexibility of this method.

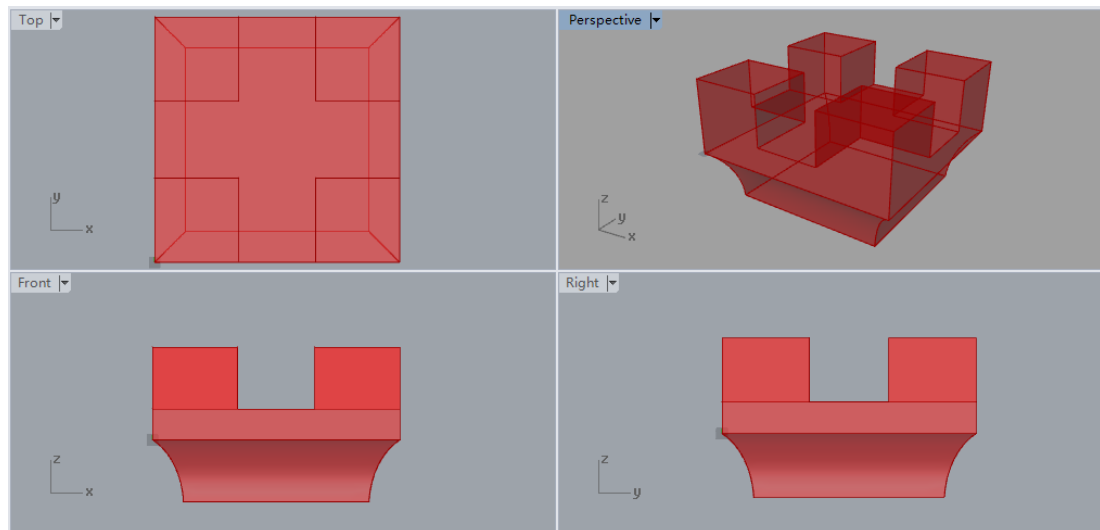


Figure 228. Optimized test of *lu dou*

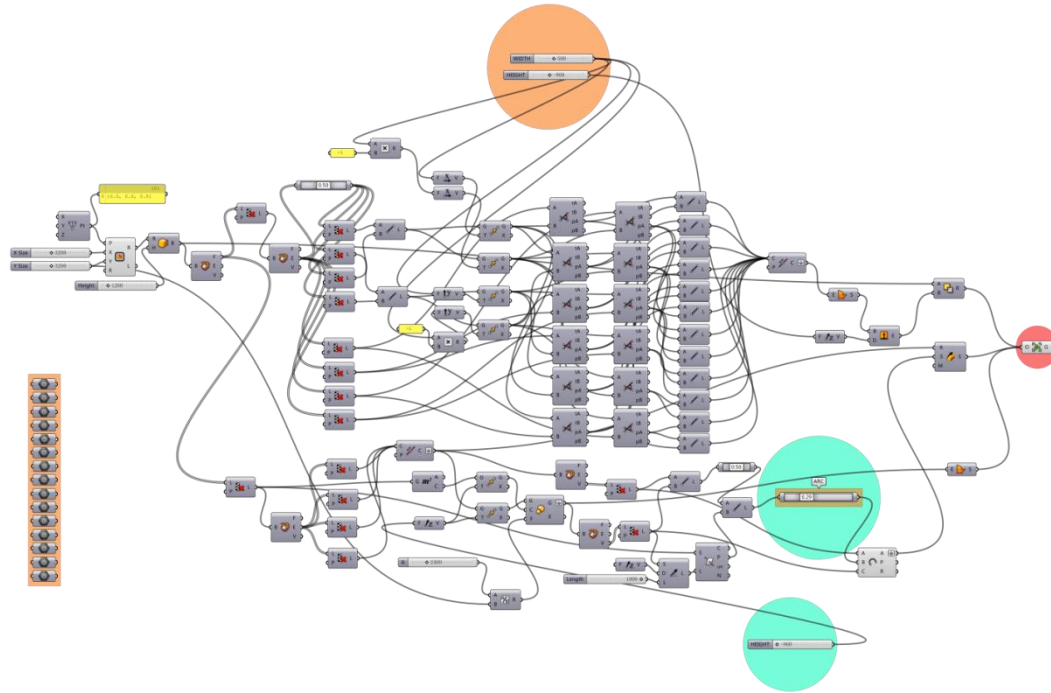


Figure 229. Modelling process of the optimized test of *lu dou*

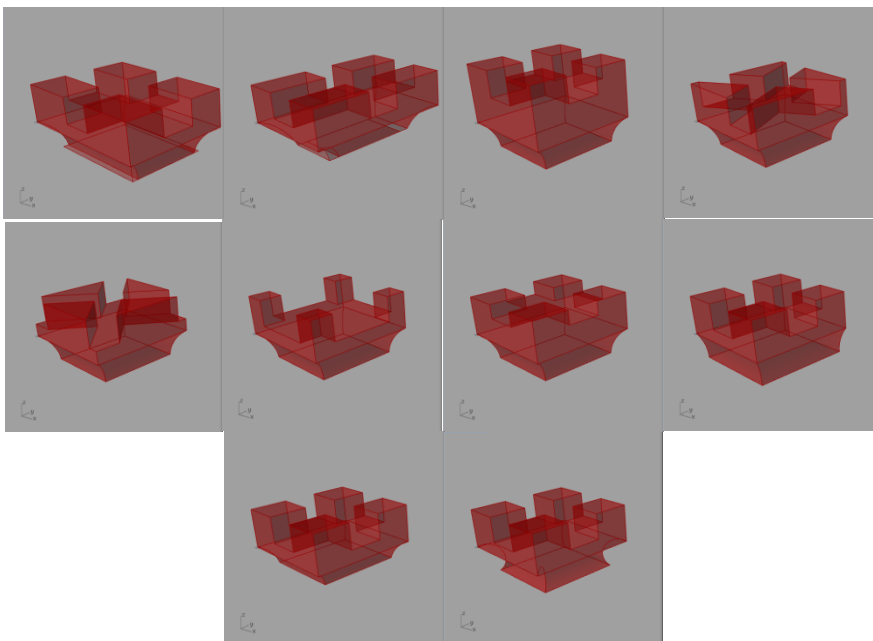


Figure 230. Variations of the optimized test of *lu dou*

In the sense of successfully presenting the *lu dou*, the attempt achieves the goal of “parametrics serve the style” adequately. Since other types of *dou* share similarity

with *lu dou*, they can be built up follow this attempt. Although *gong* and *ang* are not similar as *dou* in geometry, the concept used in this attempt can also be applied to them for modelling. To boost the progress, we move on to the next attempt with the focus of simplifying and optimizing the algorithm by putting the initial consideration on the available techniques.

5.5.2 Attempt 2

In the second attempt, the parametric presentation will be tested on both *dou* and *gong* with the focus of simplification and optimization options. Different from the last attempt, the strategy in this attempt is to set the available parametric techniques and their features as the primary consideration, and test how these techniques could be used to present the models. This concept could be called “technique centred” process. In other words, this is the concept that “style follows the parametrics”. In the previous two case studies, this brings problems. However, in this case study, in order to deal with the very sophisticated joint, study needs to be carried out from both directions. In this way, we can explicitly explore the advantages and disadvantages of both strategies, as well as select and combine merits from both to propose better solution.

First, *lu dou* is selected as the test target. When analysing the shape of *lu dou*, it is overall close to a cube. So we build up a box in Grasshopper as the basic shape. Then the top and bottom surfaces are extracted since they need further cut in the later process. Next, the upper part is extruded by a cuboid to get the inner cut space of the two “ears”. If the *dou* has four “ears”, then this step is repeated at the cross direction to get a perpendicular inner cut space. Then, the lower part is extruded by four cylinders to get the arch curves. The outcome is shown in Figure 231, and the modelling process is in Figure 233. When removing all the assistant shapes from the basic cube, *lu dou* can be presented as in Figure 232. Similarly, other types of *dou* can also be presented with this method. In the future, the control values and boundaries of the basic geometries need to be further defined and included into the algorithm to obtain the accurate model. In particular, the curvature of the arch requires more precise definition.

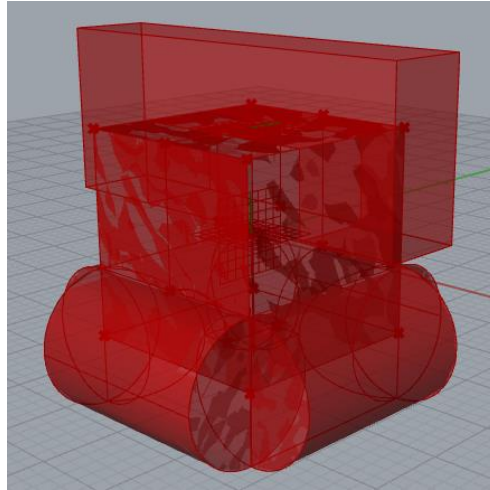


Figure 231. Approach to *lu dou* by basic geometries

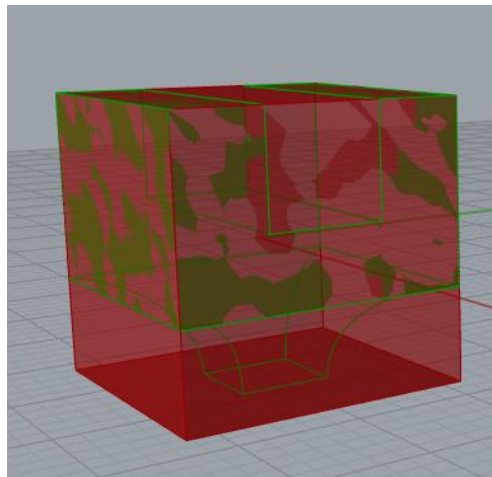


Figure 232. *Lu dou* (green volume)

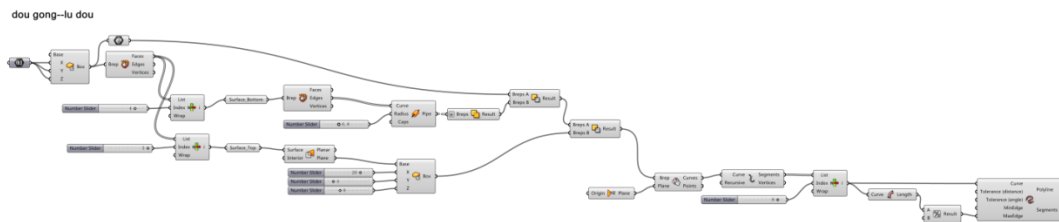


Figure 233. Modelling process of *lu dou*

After this, *gong* will be tested. In the same way as the *dou*, *gong* can be abstracted as a cuboid to present its volume. Then the key problem will be the “curve” at the

bottom. As mentioned in the digital fabrication section, this “curve” is not a proper curve, but made up of a number of line segments. So the major task is to allocate the point positions and then join them up to create this segmented line curve. First, we find out the four endpoints on the rectangle as reference. Then divide the bottom edge into two and allocate the midpoint by Arithmetic mean. Since *gong* is symmetric in most cases, we can look at half of it and then mirror the half to get the full structure. Next, we need to divide the right edge and bottom edge following the orders illustrated in Figure 212 as an example, using Divide Curve. The divisions and length of each segment can be controlled by number sliders. Then connect the points on right edge and bottom edge correspondingly and this will give the node points in between as well. Then link up the edge points and the corresponding node points to create the segment line curve. The approach is shown in Figure 234 and the final curve is shown in Figure 235. The modelling process is shown in Figure 236.

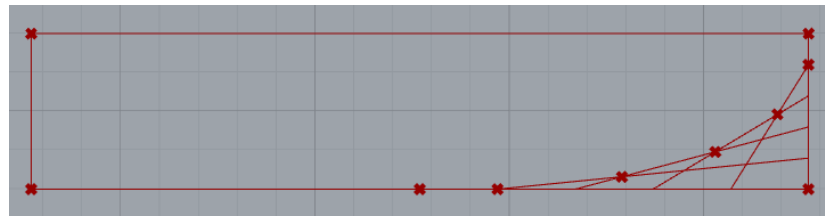


Figure 234. Approach to *gong* by divide curve

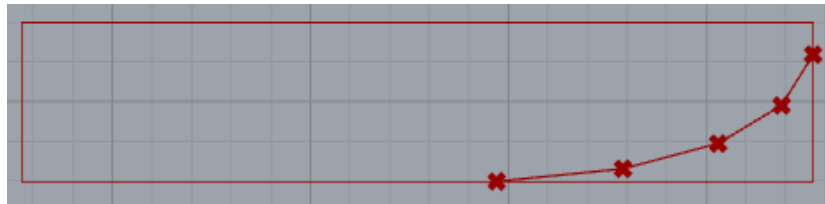


Figure 235. The curve of *gong*

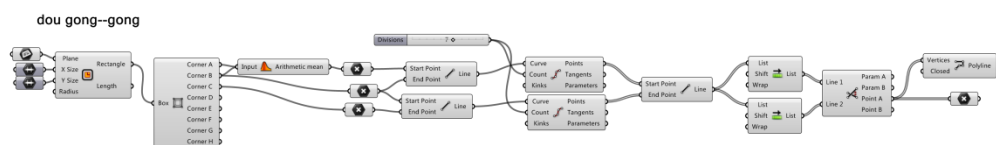


Figure 236. Modelling process of the curve of *gong*

In this attempt, we simplify and optimize the algorithm based on the most adequate techniques available and substantially reduce the complexity and workload of the algorithm. The tests achieve the overall configuration of the joint elements although more detailed and strict definitions and boundaries of the parameters are required further for accuracy. This will be a sophisticated and long process but predictable. Together with the first attempt, when combining the merits of both attempts, the algorithm could be clear, efficient, logical, powerful and controllable, while the workload is acceptable. After these two attempts, in principle, all the individual elements can be parametrically presented. Therefore, we terminate the modelling of individuals here and move on to study the overall composition of all the elements and their relationships.

5.5.3 Attempt 3

In the last two attempts, both “outcome centred” and “technique centred” concepts are considered to figure out the possibility on presenting individual elements of the joint. But to build up the complete joint, as we investigated in the digital fabrication section, the step of assembly is required. So in this attempt, the focus is shifted from single component to the overall composition consisted by all components and their relationships.

Firstly, we build up the algorithm to present *Cai* (see Figure 237, modelling process see Figure 238). The concept of *Cai* is always utilized in all the case studies for all the components, which unifies different elements being consistent and parametrically.

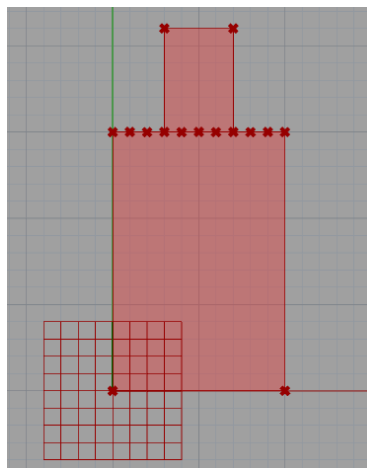
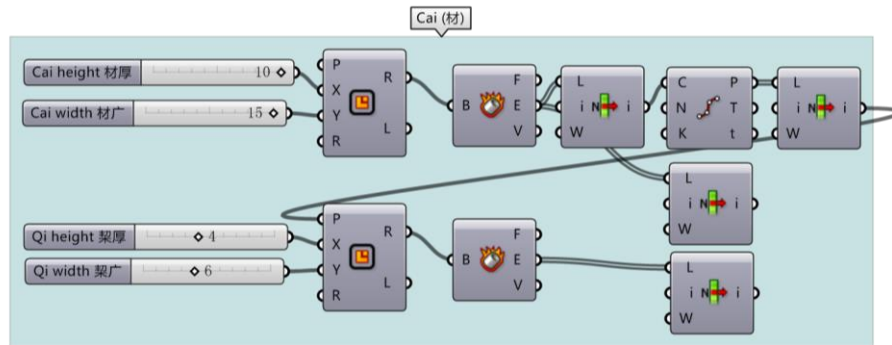
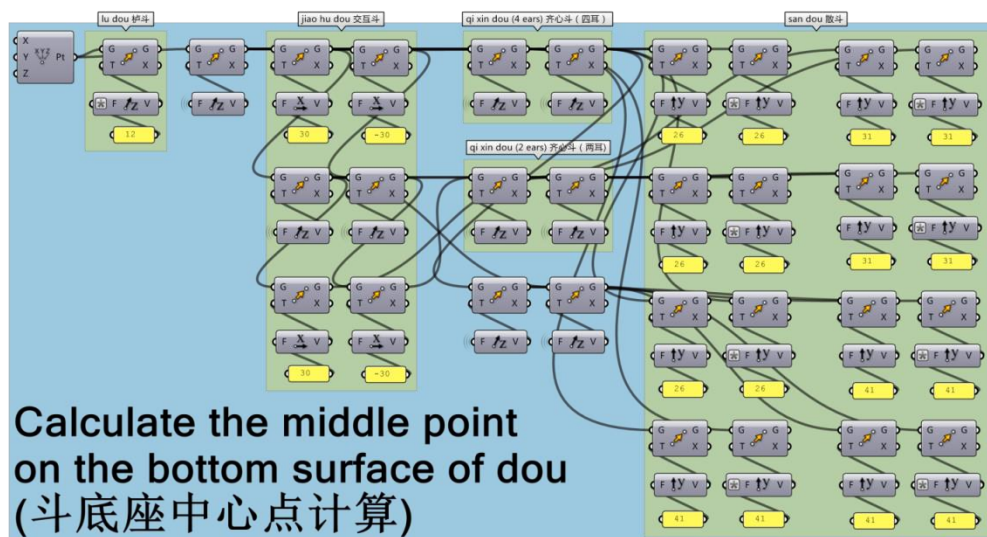


Figure 237. Attempt 3 *Cai*

Figure 238. Modelling process of *Cai*

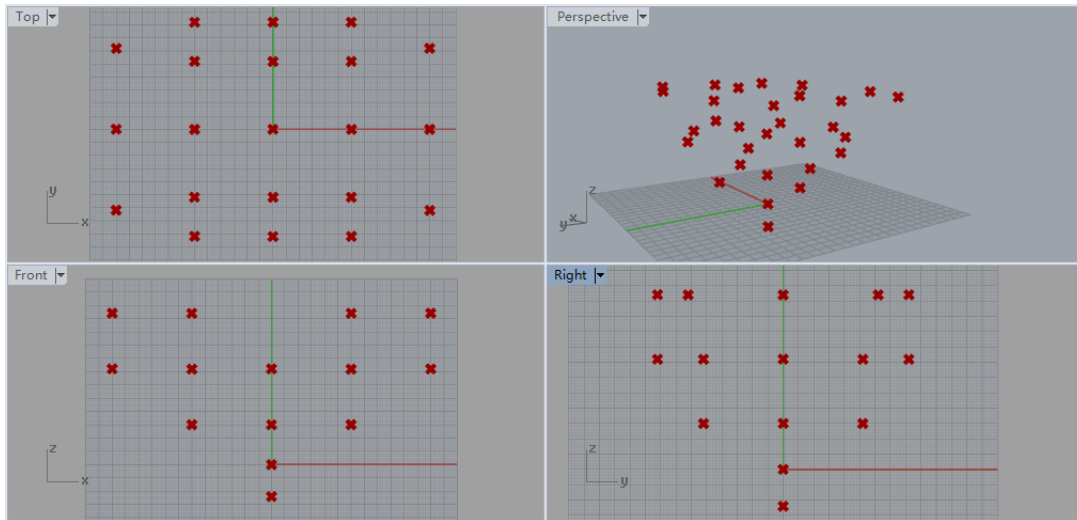
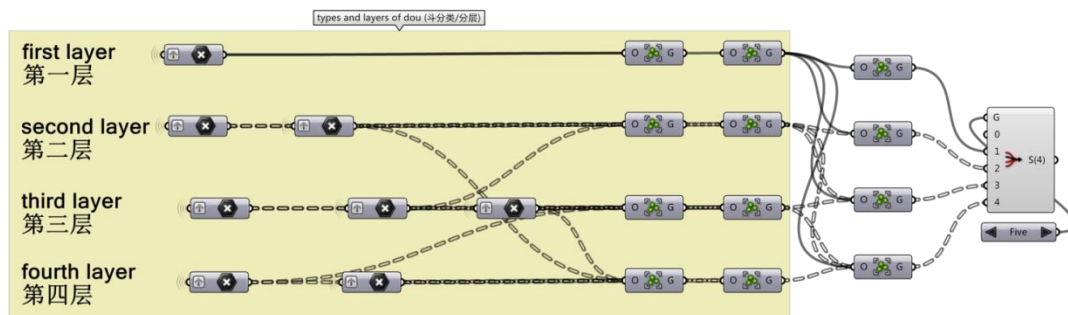
Next, the composition of all the components needs to be allocated. In the joint, *lu dou* is the base block of the whole structure. And other types of *dou* support or connect *gong* and *ang*. Thus, the layers and positions of *dou* can be the initial consideration of the configuration. Once they are allocated, *gong* and *ang* and other components can be inserted based on such locations. Since the bottom surface of *dou* is a square (some may be circular, then we could use a circumscribed square instead), we use the middle point of the square as the reference point. The calculation of the coordinates of these middle points is required as shown in Figure 239. They are managed in five categories: *lu dou*, *jiao hu dou*, *qi xin dou* (4 ears), *qi xin dou* (2 ears) and *san dou*. Although they are grouped in five, their allocation relationships are linked together rather than independently.

Figure 239. Calculation of the middle point on the bottom surface of *dou*

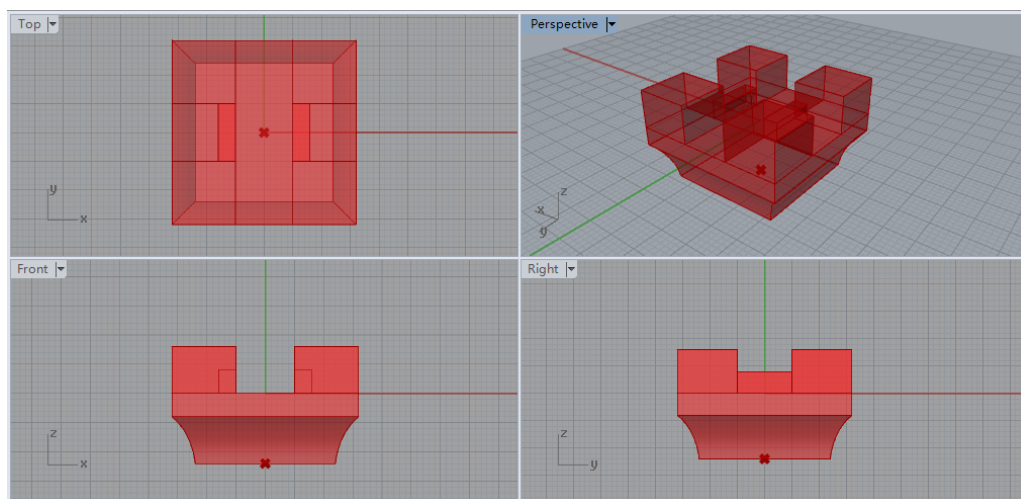
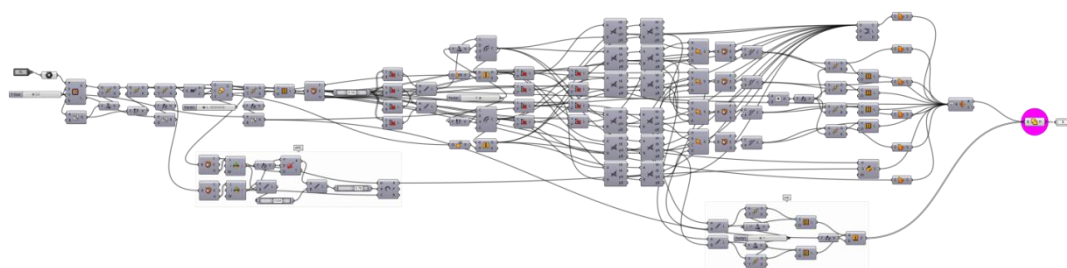
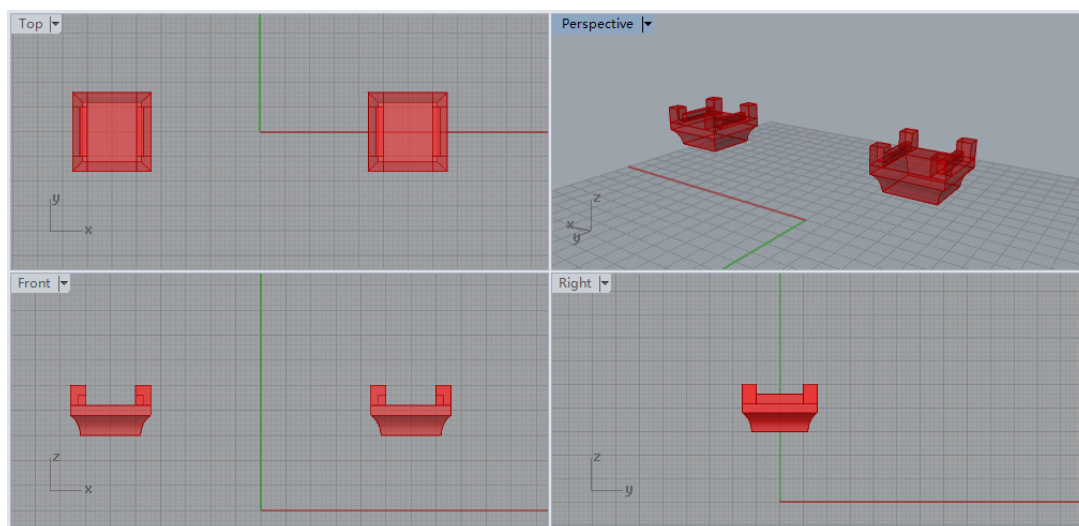
After this calculation, these points are exported. According to the digital fabrication process, the assembly layers of the joint are illustrated in Figure 240. Following this, if we only look at *dou*, they can be stratified into four layers. From the very bottom, it is the first layer of *lu dou*. The second layer is *jiao hu dou*. The third layer consists of *qi xin dou*(4 ears), *jiao hu dou* and *san dou*. The fourth layer is *qi xin dou* (2 ears) and *san dou*. These allocated points are shown in Figure 241 and the modelling process is in Figure 242.



Figure 240. Layers of the joint components

Figure 241. Layers of the middle points on the bottom surfaces of *dou*Figure 242. Modelling process of the four layers of *dou*

After this, the four types of *dou* are modelled (a series of figures are shown below with their modelling process). In different layers, the types of *dou* may appear as repetitions referring to the last step. But here we only show each type once. To keep the algorithm clear and logic, each type of *dou* is grouped together as a cluster into each layer (see Figure 251). Then they are allocated into this composition based on their corresponding points as shown in Figure 252 .

Figure 243. *Lu dou*Figure 244. Modelling process of *lu dou*Figure 245. *Jiao hu dou*

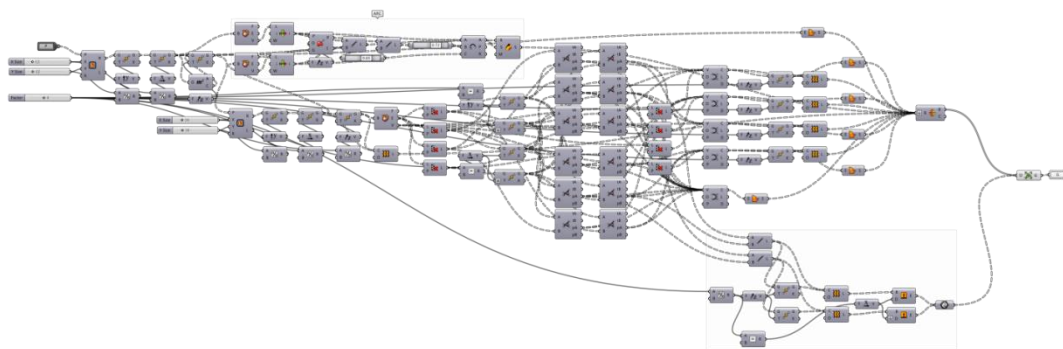


Figure 246. Modelling process of *jiao hu dou*

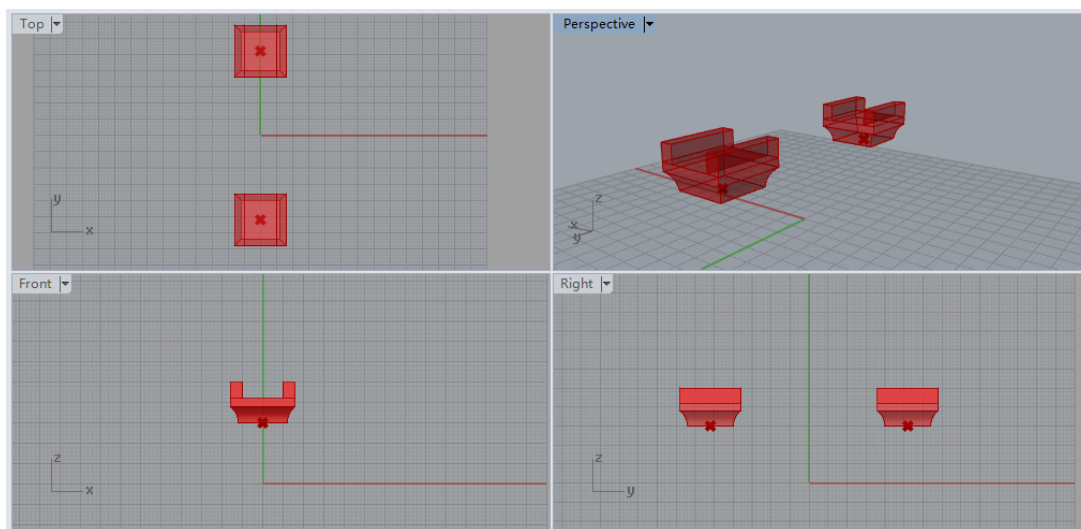
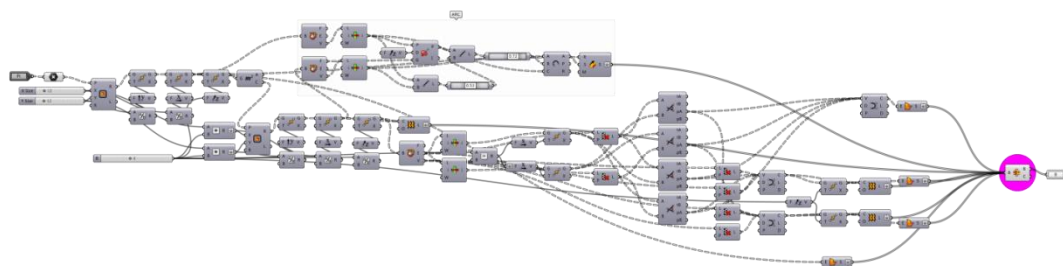
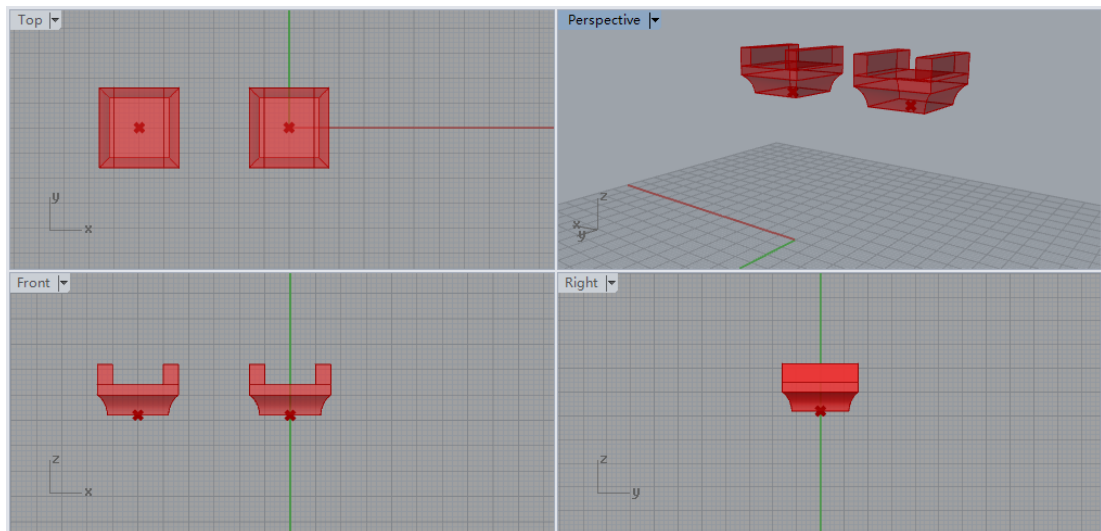
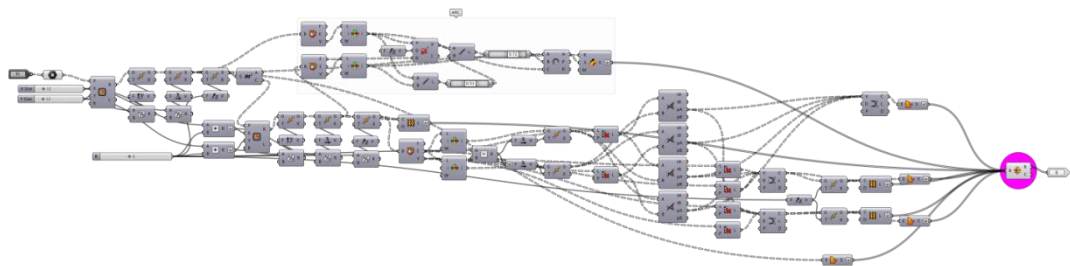
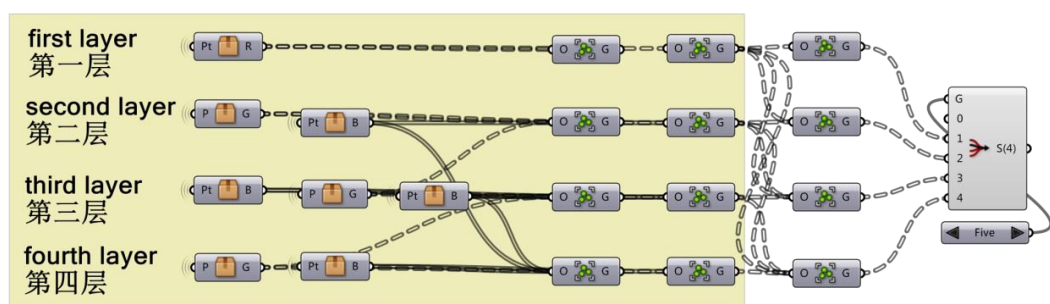
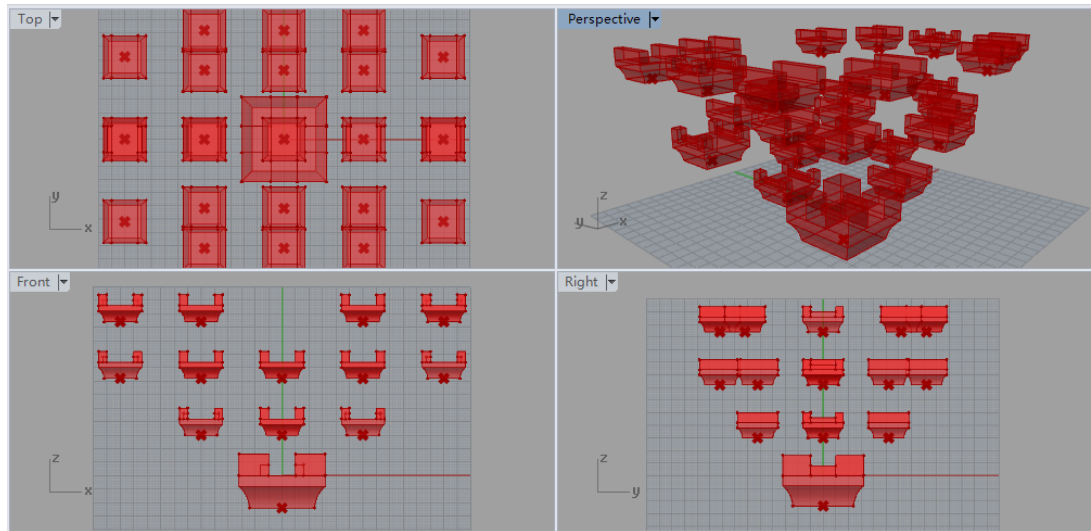


Figure 247. *San dou*



Figure 249. *Qi xin dou*Figure 250. Modelling process of *qi xin dou*Figure 251. Clusters of the four layers of *dou*

Figure 252. Layers of *dou*

Until now, the composition of all types of *dou* is completed (the complete modelling process is shown in Figure 253). Then all the rest components can be inserted based on the positions of *dou*, as shown in Figure 254.

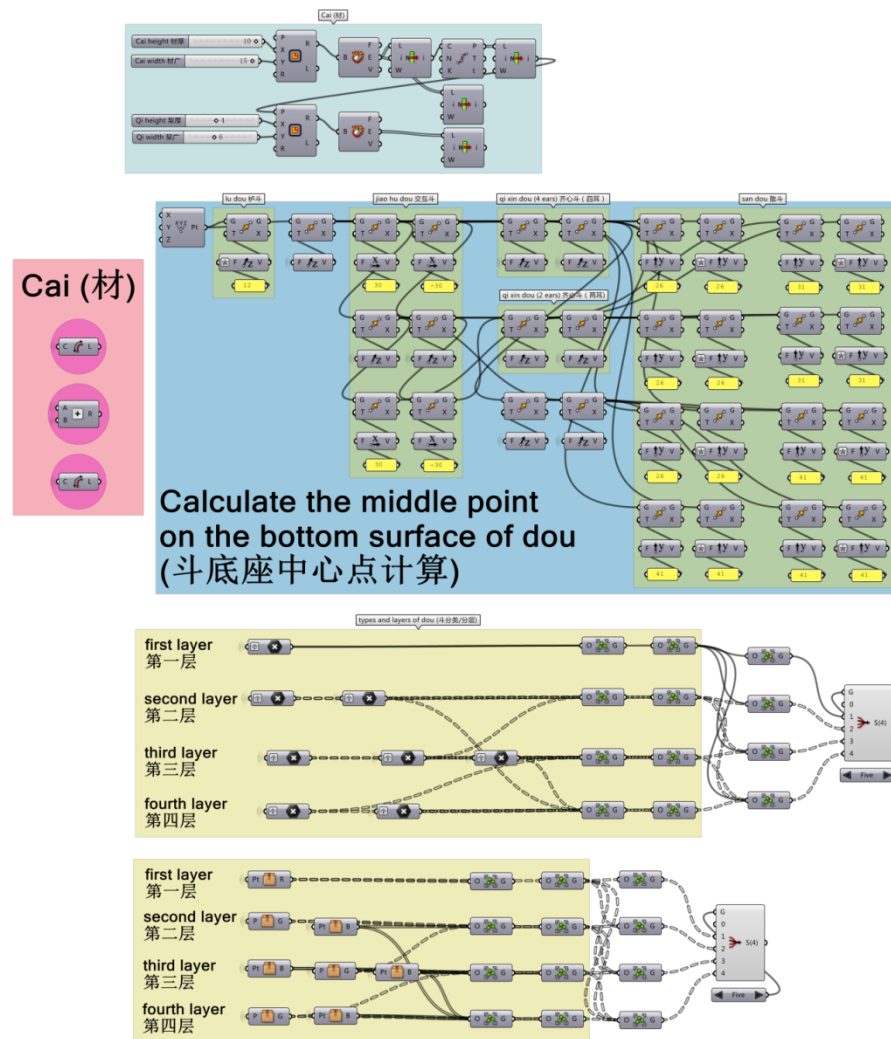
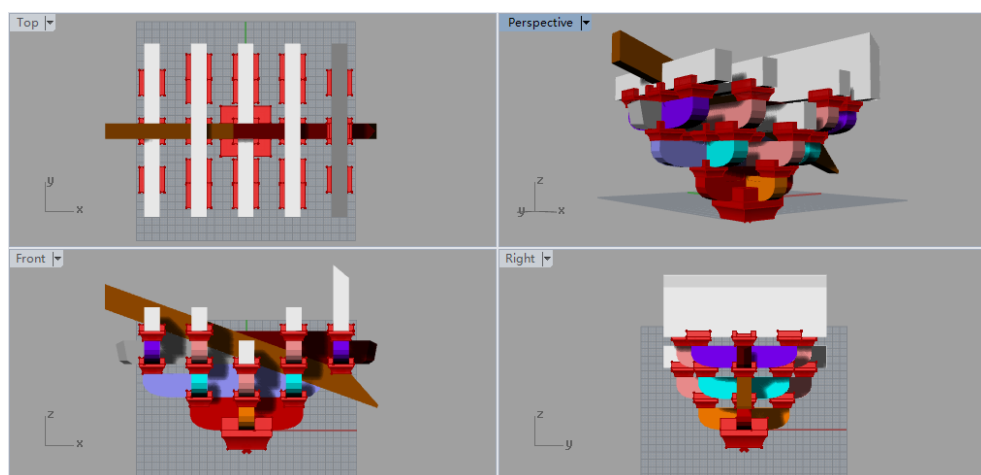


Figure 253. The complete modelling process of attempt 3

Figure 254. The complete *dou gong* in attempt 3

In this attempt, based on the initial consideration of the positions of *dou*, the relationships of all the components are studied by stratifying them into layers. Although we only demonstrate one example of five *Pu Zuo* joint here, this is a good foundation to popularize such methodology to other types of the joint.

5.5.4 Discussion

In the bottom-up method of parametric modelling attempts, both “outcome centred” and “technique centred” strategies are studied and their merits are summarized. Then the overall consideration of the configuration and inner relationships is carried out. In general, although limitations exist in the three attempts, they consistently and effectively figure out an optimized and logic approach to parametrically represent the joint. The omissions and corresponding potential solutions are also suggested respectively. This methodology can be transferred to any other types or sizes of the joint. Although *dou gong* has many variations, the essential structure and design concept remain highly similar over times. Therefore, the research established here would benefit the future research of the details of the joint, as well as the general timber frame structure. Apart from these, we also observe the complexity in algorithm and modelling processes. Similar as the last case study of the section, when reaching a certain level of complexity and difficulty, the support of the software and interface functions becomes more important. In this way, the algorithm can be presented adequately and the act of thinking can be presented logically and explicitly. And in turn, this methodology can be utilized in assisting the practical designs. In this case study, we continue to make clusters to keep the algorithm clear and logical. But to carry out future research with more details and complexity, proper add-ons and other types of support to the interface could be beneficial.

5.6 Discussion, conclusion and future work

Compared with conventional handmade techniques, obvious advantages are demonstrated in this case study with the digital techniques. When producing the joint by digital fabrication and parametric modelling, the process is efficient such as the components can be reused in other types of the joints if they share some parts the same, without doing the “analysis, assumption, checking and modelling” process again. And when the overall scale needs to be changed, the digital models can easily achieve this. What is more important, industrialization is the trend to gradually replace handmade method to increase the productivity, standardize the process and optimize the outcome quality. And indeed, today there are very few knowledgeable and experienced carpenters who can be found in this area which has led to a gradually disappearance of this kind of traditional construction. Thus our technique

using digital representation and fabrication could be used as an alternative to maintain the traditional style and skills for the future generation and research purposes.

Benefits from this case study are twofold: the findings could be used in future research and practise; also, it could be instructive in teaching and education. To understand traditional Chinese architecture, it is impossible if the *dou gong* is not closely studied. During the process of digital representation, fabrication and assembly, as well as the parametric modelling, a detailed 3D joint has been derived from the 2D pictures and text descriptions of the rulebook. This is a great help to understand explicitly how it is built up from its component parts, and in turn to understand its design concept and mechanism.

This is the basis of future work on how to generate new designs that respect the old traditions. And it is only through the physical model assembly process, that the importance of the traditional *sun mao* (tenon-mortise connections) could be found, which cannot be detected in any virtual environments. Also, the weakness of the ears of the *dou* is observed during the fabrication and assembly of the physical model, which may be ignored if only studied in software. Apart from these points, study and understanding of traditional Chinese architecture and Chinese architecture history should be a core in the education, although almost no institutions have such module or teaching content outside China, and many institutions inside China do not produce effective teaching materials on this. And according to author's teaching experience, many young students have difficulty in understanding such a complicated structure because they may never see any extant examples, nor have enough background knowledge. So a relatively cheap and easily made physical model and the follow-up parametric modelling procedures could help them greatly. In this process, everything is not very difficult or abstract, meanwhile safe enough for those without any carpentry skills. However, the accuracy level is high enough, and the algorithm logic is clear. So the students can thus gain a direct understanding of such a complicated structure.

By completing the digital fabrication and the parametric modelling process, several difficult and unclear aspects of the *dou gong* have been better understood. The important outcomes of the parametric representation and digital fabrication techniques can be summarized as:

First, clarity is brought to the understanding of the role and modus operandi of some elements which are not fully described in the rulebooks. This contributes to the knowledge that omitted or unclear in *Ying Zao Fa Shi* based on the experimental results. Thus, the annotation to *Ying Zao Fa Shi* could be further improved.

Second, the order of assembly is better understood both physically and virtually.

Third, the vital importance of the small supportive parts such as ears of the *dou* in the whole structure are better appreciated. In future research, certain reinforcement might be included to give extra support to these weak parts.

Fourth, in using a paper 3D printer, differences are examined in the modelling tolerances compared to using other forms of 3D modelling materials. Also evidence from this result is that, paper, as a modelling material is very appropriate, and for this purpose better than other materials used in digital fabrication and may give a better option in terms of being a sustainable material choice.

Fifth, what is more significant is that the 3D model allows development of the other aspect of the study, that of a parametric interpretation of *dou gong* by clearly understanding the inter-relationships of the individual elements. And this contribution has been proved in the parametric attempts to be valuable in the algorithm and modelling.

Sixth, this is an alternative way to appreciate and maintain knowledge and understanding of traditional value and styles.

Seventh, the findings of this case study could also be useful in architectural education and education more generally.

By completing this case study, it is proved again that the concept *Cai* could link together all the parts of a building and this is a significant rule in the parametric representation of traditional Chinese architecture. In addition, further to the last case study of the section, another methodology is studied such that breaks down the complicated problem into parts and find out potential solutions from different origins of thinking. Then by optimizing and combining the merits, the aim will be achieved. This bottom-up method could also be used to the research of other complicated and sophisticated structures. Also, the software limitations are observed. And current solution and future development suggestions are discussed to enhance the digital techniques.

By approaching the design and construction of the *dou gong* in this bottom-up approach, problems raised in the top-down approach are also successfully resolved. This is an important step in the overall research of digital interpretation and recreation of traditional Chinese architecture. Additionally, the assembly of a physical joint from digitally fabricated components allows a greater understanding which complements the purely digital modelling that has been undertaken in the early phases of the research. Overall the value of the *dou gong* has been better understood through different tools that contemporary digital technology can offer. Consequently, the understanding of the *dou gong* is the basis for the future research, for example, the interpretation of the unique roof, in terms of why the extent of eave projection could achieve up to 4 meters and why the raising degree of the roof permits light to penetrate to the interior of the building despite the wide overhang (Liang, 1985). In this way, the traditional Chinese architecture will be better

understood and the traditional value will be well respected in contemporary time. This is a firm foundation for inspiration of the new Chinese style designs.

Chapter 6 The integrated models of traditional Chinese architecture

After the three case studies, the floor plan, the section and the joint are studied respectively. Since they are not independent and closely linked together with each other, the relationship of these three aspects is worth discussing in order to enhance the understanding to traditional Chinese architecture as a whole. In this chapter, the integrated models will be demonstrated based on the research findings in the three case studies.

When we recall the algorithms in the floor plan and the section case studies, we make them as clusters in the control panel. Now if all the clusters presenting different components are connected together, as shown in Figure 255, a complete set of the clusters in the control panel is produced. An example of the integrated model generated by this set of algorithm is shown in Figure 256. In particular, the parameters setting need to be consistent in different clusters. For example, if in the floor plan algorithm, Grade One *Cai* and ten rafters are selected, then in the section part the same value of parameters are required. Here, we leave the joint layer still as a blank layer but with the correct dimension. This is because we build up the major timber frame with abstract lines to present its core structure without considering the volume of the material. Thus, it is a wire-frame building. In practical cases and future studies, we can extrude the lines to pipes and rectangles with other details on them. But this is beyond the scope of this research. But this does not apply to the joint since we have to involve the volume of the joint to present it. Therefore, the three layers are kept as a proper illustration of the integrated model, as shown in Figure 257. And this is highly consistent with the extant building Fuoguang Temple major hall shown in Figure 156.

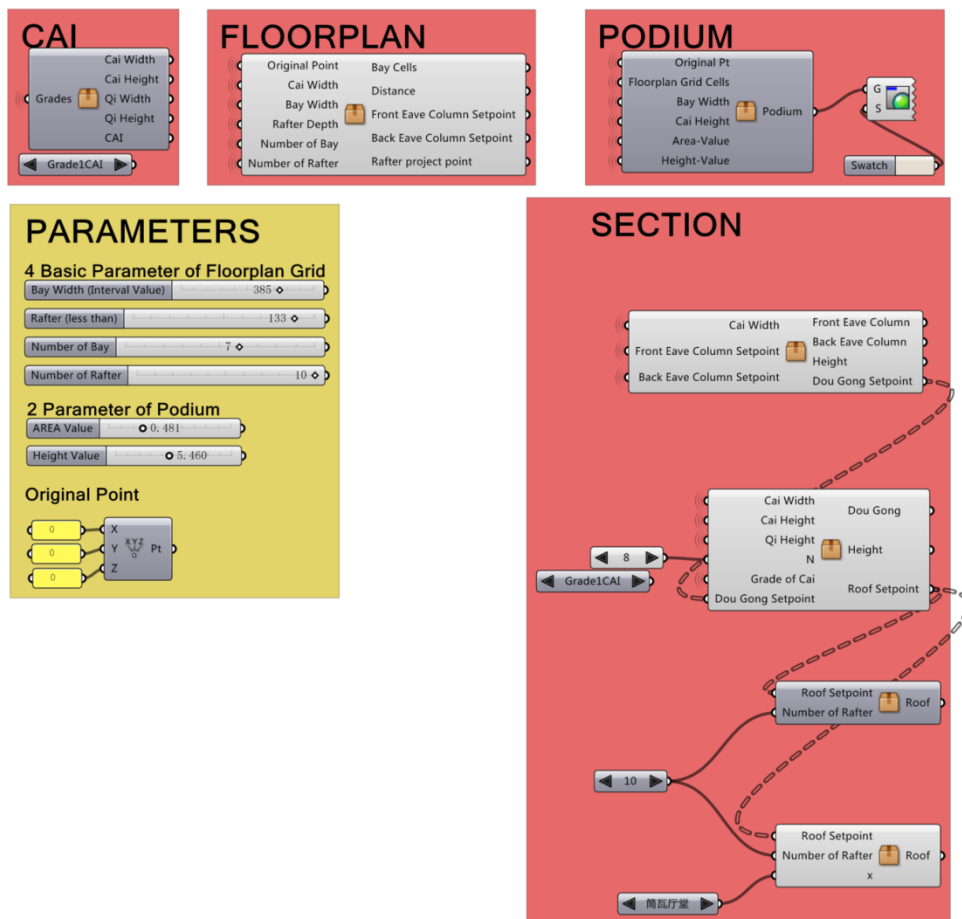


Figure 255. A complete set of the clusters including the floor plan and the section

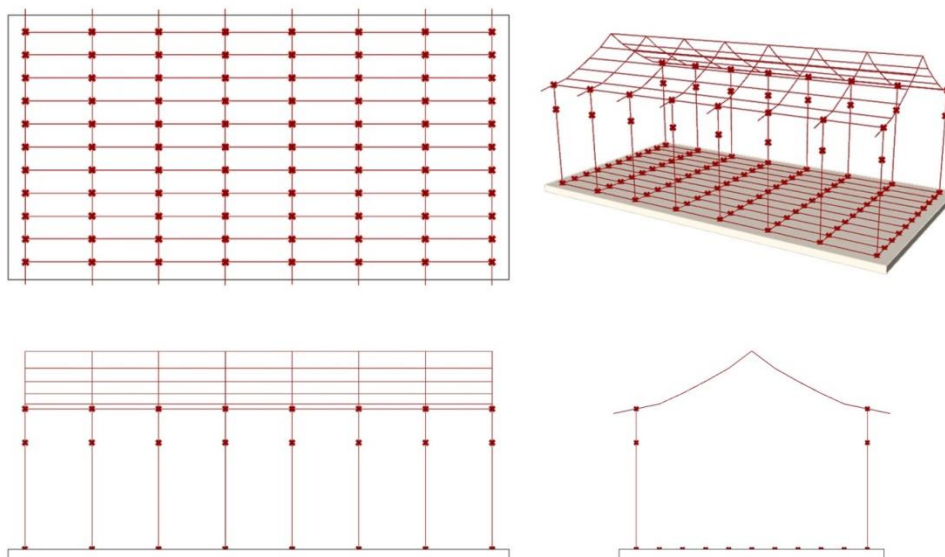


Figure 256. An example of the integrated model

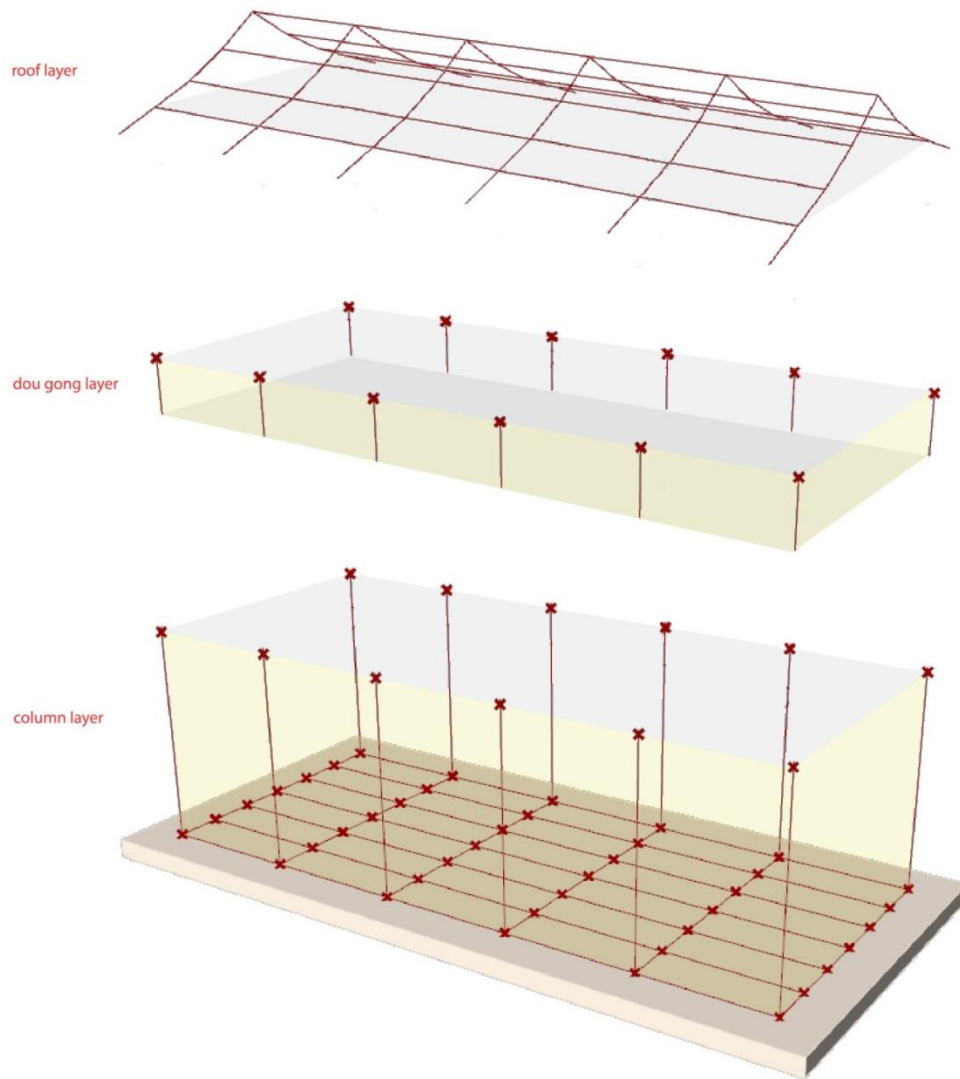


Figure 257. Three layers of the integrated model

A few variations are shown below to indicate the power of the parametric modelling in terms of the flexibility in design. In Figure 258, it is a 9-bay 10-rafter building, the grade of *Cai* is varied from Grade One to Grade Four, while the overall scale is changed. In Figure 259, it is a Grade One building with 5-bay versus 7-bay. In this case, the building width and thus the floor plan area are changed due to the changing of the bay number. Figure 260 shows the variation of the rafter number from eight to ten and in turn, the floor plan area, the section and the roof curvature are all changed. Figure 261 shows the variation of the value “N” of four and eight. As described before, this value relates to the size of *dou gong*, and therefore, the size of the joint and the section are varied accordingly.

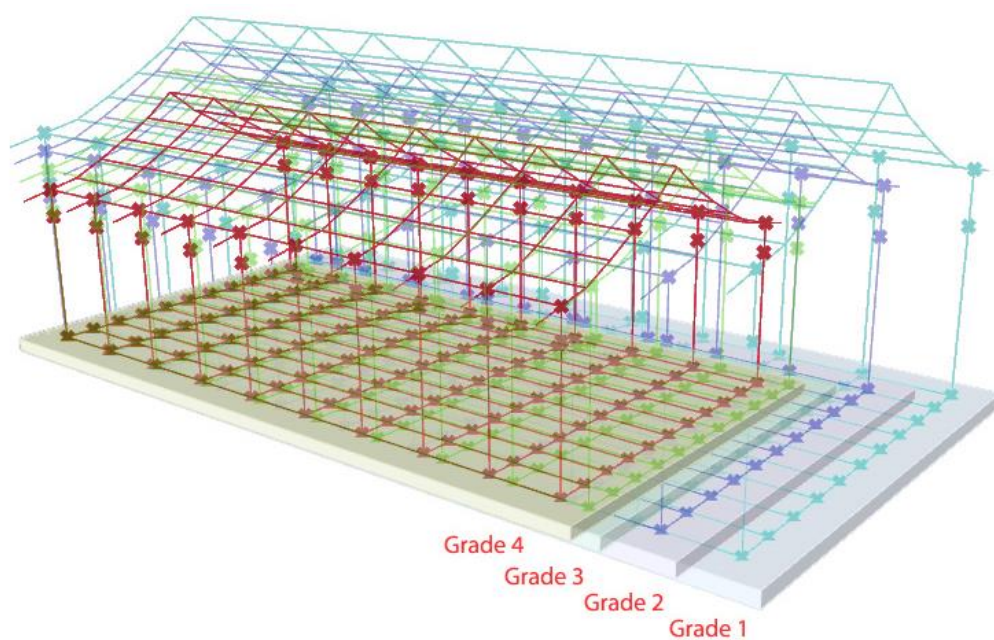


Figure 258. Variation of *Cai*: grade one to four

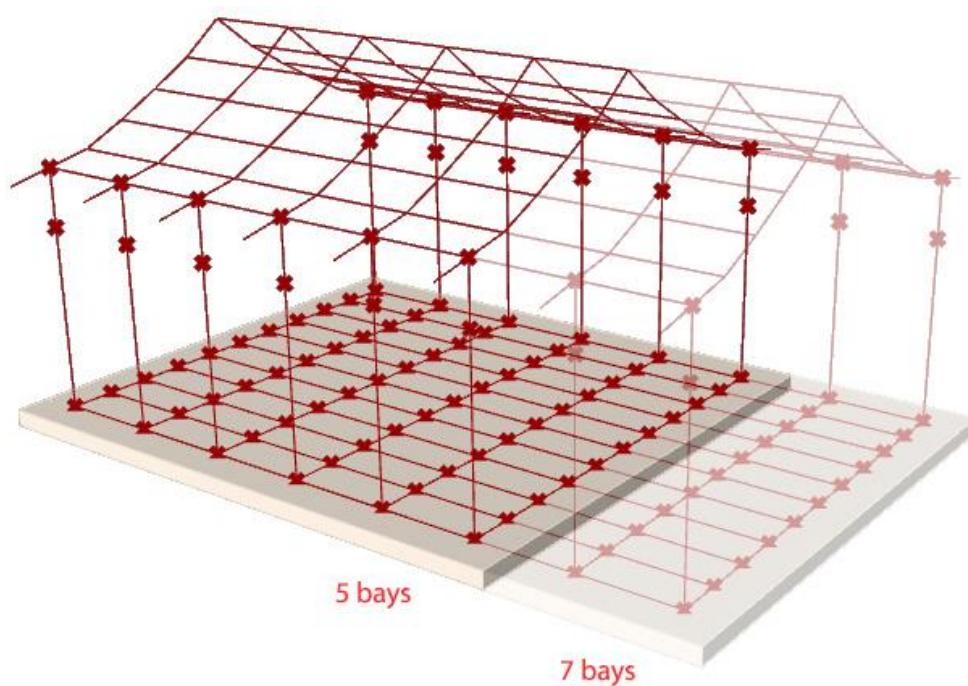


Figure 259. Variation of the bay number: 5-bay and 7-bay buildings

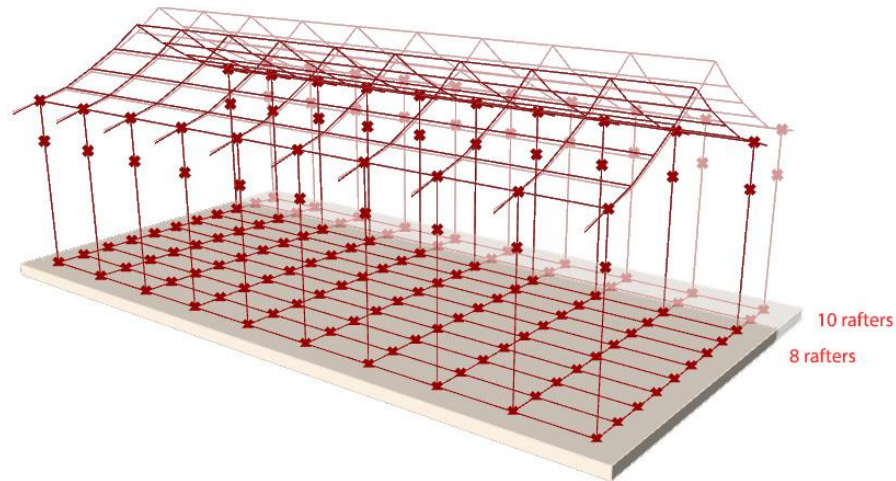


Figure 260. Variation of the rafter number: 8-rafter and 10-rafter

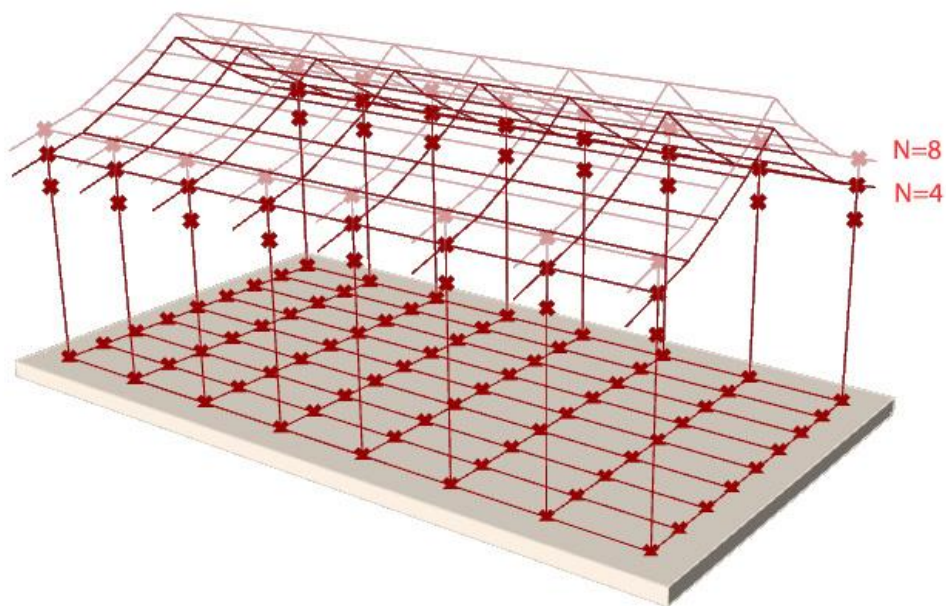


Figure 261. Variation of the value “N” of 4 and 8

We do not need to show all the variations due to all the changing parameters since they have been shown respectively in the case study chapters. But here all the integrated models indicate that parametric modelling is an intelligent and powerful design tool in generating various design options. And since the algorithms behind the output products all root back to the rulebooks, the outcomes respect and reflect the

traditional styles. In addition, the parametric method enables the process from 2D models to 3D models directly and easily. Although in the case studies, we study the two-dimensional floor plan and the section separately, when merging them together, the three-dimensional building model is generated automatically even without the study of the elevation. This is also one of the key advantages compared with the Shape Grammar or conventional methods.

Chapter 7 Applications of the research findings

In this chapter, three applications utilizing the research findings stated in the previous chapters are given. The first one is a set of new designs of the rule based floor plans generated parametrically. Then a survey of this design takes place and responses are discussed. The second is a thesis design project done by a master's degree student, which is a successful example in teaching and education. The third is a practical civic project taking place in Liverpool. This research has been a solid foundation to fulfil the client's briefing and expectations. In total, the three examples introduced here are practical experiments of the research findings, and they produce verification from another prospective.

7.1 Newly generated rule based floor plans

Based on the first case study of the floor plan, a set of new designs of the rule based floor plans are generated parametrically. There are originally hundreds of computer generated floor plans based on all the parametric variables. The process is "input definition (based on the research findings) -- generation process -- output result", and the people has no impact to change the design result. In order to guarantee the generated results are in a true Chinese style rather than fake style, the similarity with those real existing heritage buildings, or, the audience's acceptance and impression, is a key point to investigate. Therefore, a survey of this set of designs is proposed. Among all the generated floor plans, ten of them were selected. These ten are typical since they cover almost all the different variables and show a spread of the variable combinations. Then ten floor plans of the extant heritage buildings are also selected as references. These twenty floor plan diagrams are mixed up together to test whether the audience could distinguish them or not intuitively. In other words, we wanted to know whether users could distinguish real from computer generated floor plans.

The questionnaire is 9.4Appendix 2. It is designed to test different people's response to these twenty diagrams and collect their feedback. There are two parts - the first part collects data about the participants' background, including gender, age, profession and cultural background. Since this survey is on an intuitive level, different opinions may be provided according to the gender. The age factor in general relates to participants' educational level, working experience and mature level. The profession is to analyse whether architectural professionals and general publics have different sense to the same set of designs. And similarly, this sense may also vary based on their cultural background. The second part of the questionnaire provides seven questions for each diagram and these seven questions are repeated for all the twenty diagrams. Basically, the participants will need to provide their opinion

on whether each diagram presents a floor plan having the characteristics of traditional Chinese style or not, as well as whether they think the diagram is a real extant building or a computer generated diagram. After each choice of the decision, several options are given in order to understand their reasons behind the choice.

The diagrams are also attached in 9.4Appendix 2 with an automatic mixed order. The diagram titles were hidden in the survey. In the questionnaire, we not only provide options, but also collect participants' comments since the reasons and comments behind their choice are important. Especially, if they tend to disagree, this may be where wrong parameters or rules/loops occur in the parametric process in ways that we cannot predict.

The survey was initially posted online through the LimeSurvey website. The target audience could be anyone in as large a number as possible. Obviously Chinese people (culturally speaking) is a very important group since even the general public have more or less some taste of traditional Chinese architecture. And also professionals especially those with Chinese architectural knowledge are significantly important. Another important group is those with non-Chinese background but have been involved in Chinese culture and architectural field, such as foreign architects working in China. According to such proposal, the survey was distributed both in China and through eCAADe (Education in Computer Aided Design) group in Europe.

Unfortunately, the goal was hard to achieve. Since mainland China has a firewall to block overseas website servers, the distribution in China is difficult and inefficient. And in turn, the response is not sufficient as we expected. Eventually, there are over 100 responses in total and half of them are considered being valid for analysis. Although the total response is not sufficient, the results are quite unified and featured. Thus, qualitative analysis will be given instead of quantitative analysis.

The most important and unified result is that almost all the people cannot distinguish the computer generated diagrams and the real building diagrams regardless of their personal background. And people tend to think most of the diagrams are real extant buildings. Indeed, for each diagram, there are a large number of people treating it as real extant building with traditional Chinese features. And within the given choices of reasons in question two and five, each reason is selected by a number of people. Consequently, from the responses we get, the similarity of the computer generated floor plans with the real existing heritage buildings is verified to be intuitively acceptable by the audiences.

One aspect that Chinese people (regardless their professional background) and non-Chinese people have obvious different opinion is that, in question two, the reason of "orientation of locating at the north and facing the south" as a traditional Chinese feature is selected by almost all the Chinese people, while not widely selected by non-Chinese people. Although the orientation is not studied in this research, it is a commonly known tradition in China. Especially in the north part of China, for those

cities with very regular civic planning, such as Beijing, old and traditional houses such as the courtyard type houses, as well as ancient temples and palaces, all follow this character. And this also partially relates to the *feng shui* (wind and water) concept.

There is another interesting result that a number of people tend to think the diagram of Taihe hall (see Figure 293 in 9.4Appendix 2) is not a real heritage building although it is. And their reason is mainly “the dimension and scale is out of the boundary of traditional Chinese buildings”. In fact, Taihe hall is the biggest and highest level palace in the Forbidden City in Beijing. And it is one of the very few extant large scale ancient buildings in China. Therefore it may be beyond people’s normal impression.

Apart from these analyses, several respondents provided the opportunity for interview in person which provided valuable comments that are worthy of note. Two of them are selected to show here.

Person A is a Chinese female aged between 25-34 with architecture background, but without specific background in history of Chinese architecture. She thinks the set of diagrams are professional in terms of reflecting the traditional Chinese style and it is obvious that all the diagrams are ancient style buildings. She cannot recognize the dots (columns) in the diagrams, because in modern Chinese buildings columns are rarely used. Instead she thinks those dots may be decorative furniture or pots of plants. Her guess is reasonable to some degree, because to put decorative furniture or pots of plants is a kind of tradition in some areas of China in the past. We also mentioned in section 1.1.1.3 that MAD studio takes the inspiration from the Chinese potted landscape to design the Shan-shui City project (see Figure 34). Also, she points out that some of the diagrams such as Figure 284, Figure 285 and Figure 290 seem to be unreal because they lack barrier wall or partition between the two open doors at the front and back. In her opinion, this kind of open space does not maintain a very important Chinese tradition that indoor space should gather the good atmosphere for fortune. Actually Figure 284 and Figure 290 are gates of a group of buildings, and Figure 285 is a similar type with the two generated by computer. So they are not living spaces. Overall, her comments are positive and the aspects she points out could be developed for future research work.

Person B is a non-Chinese male aged between 35-50 with architecture background and works in Hong Kong for more than twenty years. His opinion of the diagrams is more or less the same as we summarized above. But he points out that instead of doing one large survey, it might be psychologically more effective to split the survey into two parts: let participants do one survey of 10 diagrams first, and then invite the same users to do a second survey later. In this way the survey looks a bit shorter and meanwhile we could also see whether the participants change their mind or not when coming back for the second part. Also, to make the survey more interesting and gather more feedback, interview in person may be better instead of the online

questionnaire. In general, his comments regarding the survey format is useful to make improvement in our future research although at this stage might not be fully feasible to carry out.

Though the survey is not a formal verification of the designs, it indicates participants' general acceptance and positive impression to the designs based on the research findings. Meanwhile, it gives direction to the possible future work.

7.2 A Master's degree project

This research has been presented in a variety of the lectures and tutorials in the MArch and MA programmes in the University of Liverpool. A few master's degree students showed their interest in this topic and developed their thesis design projects partially relevant to this research with my advices. The project done by Zuqiang Qu is especially closely related to this research. The title of the project is "Experiment of Exploring the Practical Usage of Parametric Rules— An approach for Contemporary Chinese traditional architecture heritage". He reviews this research first and refers to the algorithms and rules summarized in the three case studies to develop his design ideas, as shown in Figure 262. It is an exhibition centre with traditional Chinese features built with bamboo. The floor plan and section (see Figure 263) reflect the styles in *Ying Zao Fa Shi*. Based on the research findings in the first two case studies, he makes variations to the algorithm and generates irregular floor plan shape, followed by a height-changing section and the roof. Similar to the author's delivery of the *dou gong* in the integrated model, he does not include *dou gong* directly into his design due to the complexity. Instead, he symbolized *dou gong* as laminated wood layer and keeps the same height as the *dou gong* layer, as shown in Figure 264. In general, this project is a creative experiment of producing a new design that respects the traditional styles. On one hand, it retains the essential design concepts and rules recorded in the rulebooks. On the other hand, it produces novel attempts of the design fitting the contemporary expectations. The feedback to this project in the peer review and examination is positive which reflects the research values in teaching and education.



Figure 262. Exhibition centre (Qu, 2014)

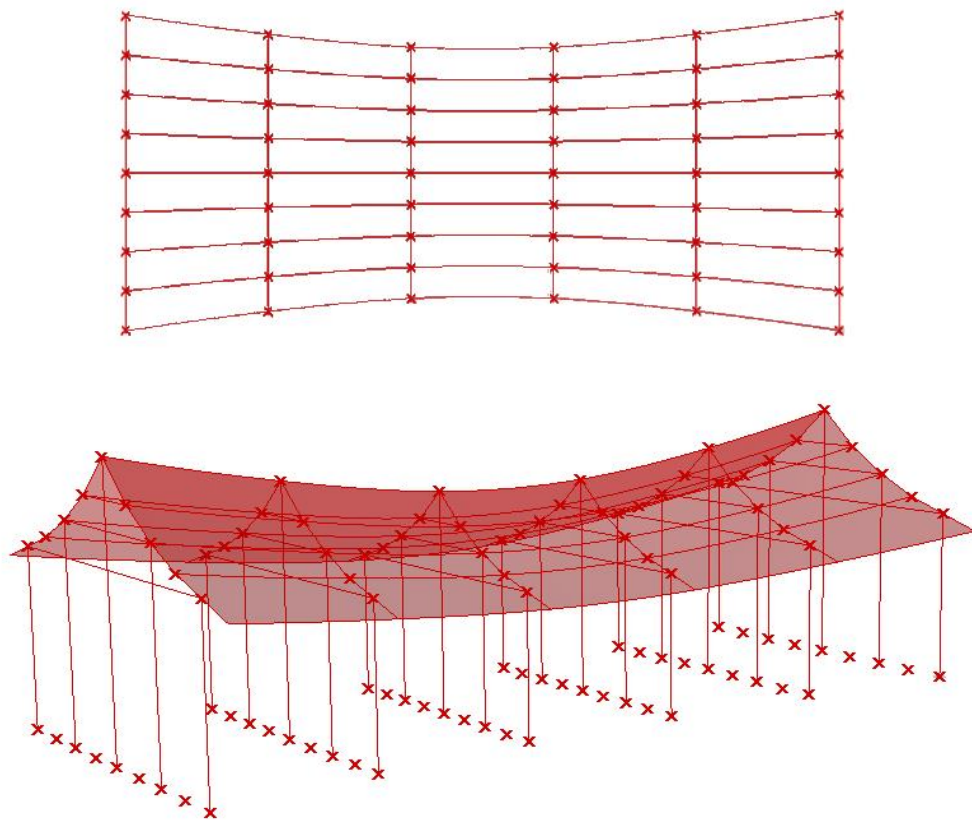


Figure 263. The floor plan and perspective view (Qu, 2014)

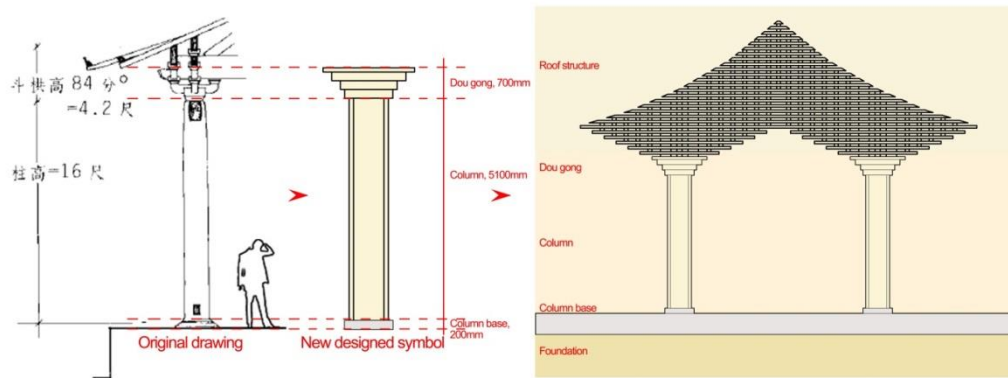


Figure 264. Symbolized *dou gong* (Qu, 2014)

7.3 A practical project of a Chinese garden

This research brings the author the opportunity to design the Chinese garden located at the Chinatown of Liverpool. This is a practical civic project and is part of the “New Chinatown Project” (Anon., 2015) proposed in Liverpool. The project started since 2015 and currently is in progress. The site of the garden locates opposite to the Liverpool Cathedral (see Figure 265) and is currently an empty green land (see Figure 266). The major plan of the “New Chinatown Project” will be a commercial building block (see Figure 267), and next to this block will be the Chinese garden.



Figure 265. The site location of the Chinese garden



Figure 266. The site of the Chinese garden



Figure 267. The commercial building block next to the garden site

In the briefing, the client hopes this garden would have the sense of Chinese tradition and reflect the Chinese style in architecture and landscape. The garden is proposed to open to the local public and host events when necessary. Therefore it requires the scenery as well as the functional buildings. The traditional Chinese gardens are internationally famous, such as The Humble Administrator's Garden (see Figure 20) and The Lingering Garden (see Figure 21) introduced before. The pattern of the Chinese garden has a long history. The definitive literature on the Chinese garden was written in 1631 by Cheng Ji, named *Yuan Ye* (Ji, 1631). This book has been translated into English as *Craft of Gardens* in 1988 (Hardie , 1988). It describes the concepts and spirits of the Chinese garden design. Although the pattern and styles of the Chinese garden are out of the scope of this research, they are generally studied since they are closely related to the traditional Chinese architectural design. And this

topic could be a potential future work to extend this research since parametric tools have unique strength in expressing pattern designs.

There are initially five proposed designs, which all take careful consideration of the garden pattern, and how the pattern relates to the parametric features of each individual building inside the garden. The first two slightly exceed the site areas since the site is confirmed later as only the irregular green land as shown in Figure 265 rather than the whole green land. But the change is made quickly based on the parametric pattern concept. In the third proposal, the lake occupies the major land area so is not convenient for hosting events and the water system does not flow smoothly. The fourth proposal changes the design of the water system and is generally approved by the client. And based on this, in the fifth proposal, more functional buildings are included. These buildings are designed based on the research findings in the three case studies. And the parametric design method gives the significant flexibility and variations in the design process. Since this project is still work in progress and details are not completed yet when this thesis terminates, here we only show a few general rendering effects.



Figure 268. Design proposal 1

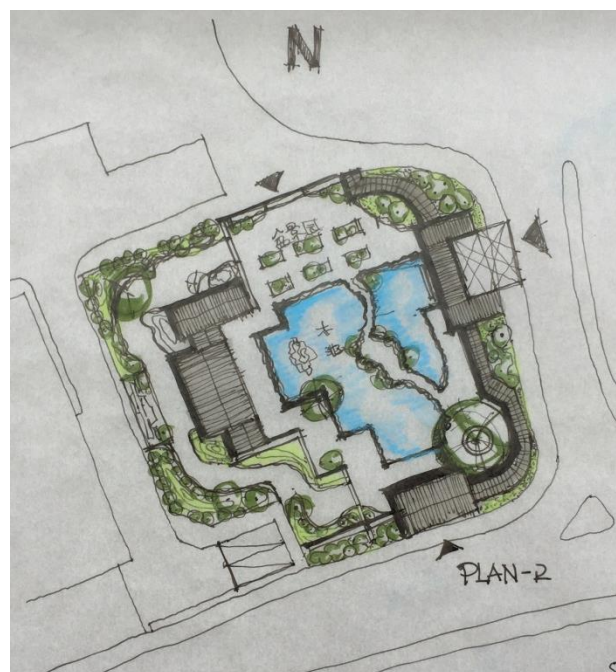


Figure 269. Design proposal 2



Figure 270. Design proposal 3

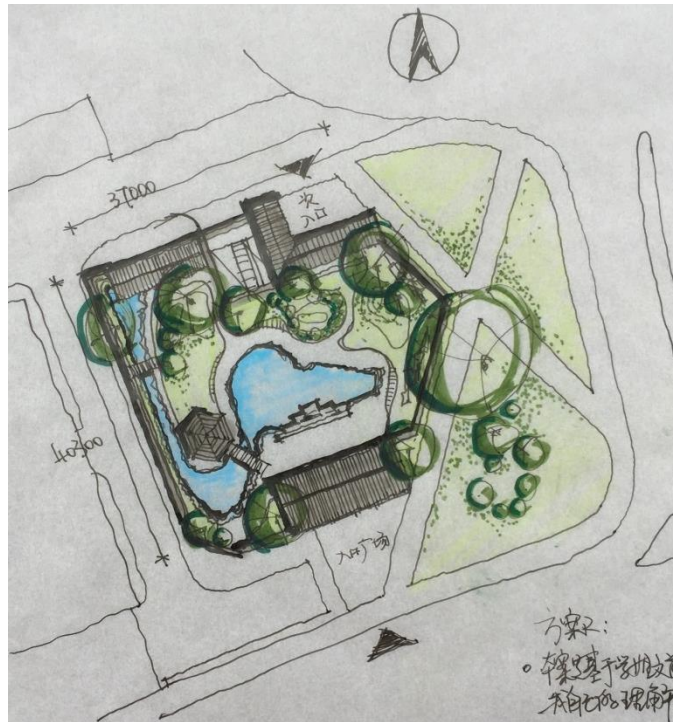


Figure 271. Design proposal 4

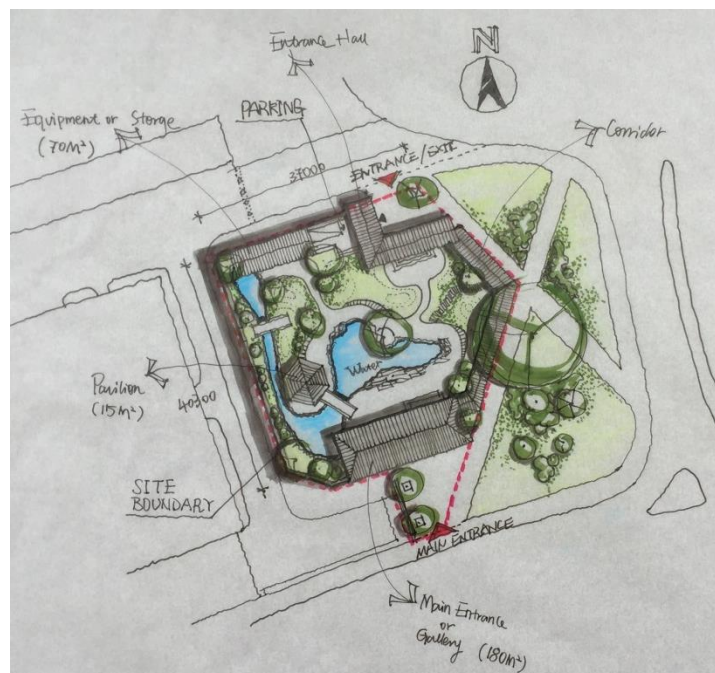


Figure 272. Design proposal 5



Figure 273. Overview of the garden



Figure 274. Major entrance of the garden



Figure 275. Second entrance of the garden



Figure 276. Scenery view inside the garden 1



Figure 277. Scenery view inside the garden 2

This practical project gives an opportunity to verify the research findings here. With the study of the garden pattern and the algorithm that has been built up in early chapters, flexibility in design is obvious. Whenever the change is required, it is possible to provide a number of variations in a short time for the client. This enables the optimization process to be efficient and competitive. Also, various combinations of the buildings can be generated based on the framework built up in the early chapters. This provides more options for the further selection based on the functional requirement. Additionally, since this research roots back to the authentic traditional Chinese style, the design based on it also reflects the authentic traditional Chinese style, which is an important reason to get positive feedback from the client. And during the future development process, the research outcomes will be further enhanced also with the expectation to gain practical feedback. Therefore this project is an example that how to utilize the digital tools to revive the tradition and meanwhile during this process evaluate the digital techniques.

Chapter 8 Discussion

In the end of each chapter, discussions and summaries are provided regarding the specific contents. So here we will not repeat the statements of each issue. Instead, the discussion at a macro scope will be given to overall review this research. In particular, the comparison with Shape Grammar approach and conventional interpretation would provide a horizontal evaluation to this research.

8.1 Comparison with Shape Grammar approach

As introduced in the previous chapters, there are parallel research in the Shape Grammar approach to the floor plan (Li, 2001), section (Li, 2001) (Li, 2003), roof curvature (Li, 2001) and *dou gong* (Wu, 2005). In the research, Li derives the process with initial symbols and a set of rules, and then the design rules act on the initial symbols repeatedly or by a certain sequence, resulting in a final design. Following each typical set of rules will result in one corresponding final design. Thus Shape Grammar generates a language of design. How and in what sequence the rules applied makes up the so called grammar.

Compared with Li's research, one advantage of the parametric method is the ease with which the process can be extended into three dimensional modelling with different combined selection of floor plan, section and roof type, as shown in Chapter 6. For instance, the intersecting points in the floor plan which present the grid of bays could be the column locations when combining with the case study on the section, without reconsidering the sequence of the relevant rules in Shape Grammar. Then, the two dimensional representation of architecture through the plan and section will form the three dimensional parametric model. During this process, there is even an additional benefit. Although only two factors (floor plan and section) are considered while elevation is not initially included into the consideration, actually the building could be generated. Thus, the elevation is "automatically generated" with the completion of parametric floor plan and section. This is a foundation for the next step research on elevation. Indeed, there are proportions and relationships that exist in the elevations (Wang, et al., 2011). But even without further research, in principle, this automatically generated elevation should reflect the traditional features since the width, height and roof factors are all bounded and well defined by the algorithm in the floor plan and section. On the other hand, if all the attempts are limited in two dimensional planes, it makes the features of traditional buildings unclear to observe and relationships in three dimensional representations cannot be well studied. As architecture is always three dimensional, the overall view is always important and thus, the tendency leading to three dimensional presentations is non-neglected.

It could be argued that Shape Grammar method could be used in three dimensional presentations. But in this particular case of study on traditional Chinese architecture, as Andrew Li says "...I emphasize the novel technical challenges it presents: text as a primary source, combinations of symbolic description and drawings, the incompleteness (to modern readers) of the text, etc..." (Li, 2015), the technical challenges included in the grammar (sets of rules) make it difficult to present three-dimensionally. As shown in Li's research (Li, 2001), to reach a final design in two dimensional plane, there are many steps including the definition of the rules and sequence of the rules. To add in another dimension, there are a series of factors to consider. For example, in which step a new single rule (defining the third dimension) can be added in? The new set of rules (defining the third dimension) also has its sequence, should this set of rules be added in as a whole or alternately with the existing two dimensional rules? Currently there is not enough evidence to show the convincing answer.

Based on this discussion, the second advantage can be observed that in parametric modelling, it does not strongly depend on the sequence of the rules (here the rules mean the Shape Grammar rules rather than the rules described in rulebooks). When using Shape Grammar rules to represent ancient rules, the sequence is one of the key factors. While in parametrics, although to build up the algorithmic logic there is a sequence in parameters' arrangements and boundary conditions, this is purely a technical term independent of ancient rules. For example, as shown in Chapter 5, different attempts are made on *dou gong*. Among these attempts, the sequence (as well as the selection of techniques) of algorithm could be changed, reduced and optimized based on the output requirement and this does not affect the outcome. Therefore, when getting rid of the limitation of sequence, focus could be put on the macroscopic overall view in order to get the most optimized algorithm.

The third advantage lies in the (relatively) infinite outcomes. As stated before, when selecting different combination of floor plan, section and roof type, and even more factors (such as *dou gong*) in the future, there will be different outcomes. As long as each factor is derived according to the ancient rules, the outcome of the combination is in general a representation of traditional features. There may exists some exceptions that when combining some selections together, the outcome is invalid. But to solve this, minor boundary conditions could be added in to the algorithm to filter the outcome. Additionally, as introduced in Chapter 1, the spirit of the rulebooks is "the rule of material (*Cai*)" or "the rule of standard length" with a concept that make different components of a building standardized so that the design and manufacture of different components can be done separately. Then they can be assembled together to form the building. This concept is very similar as the parametric modelling process that different factors are considered separately at first (as shown in the three case studies), since they all follow the rulebooks, later they are selected to make different combinations. And according to the similar concept, it is reasonably proposed that the exceptions will be a minority.

Andrew Li criticizes that the work presented in this research is mainly using CAD techniques helps to understand Chinese topics, that is, in a way that non-CAD techniques do not (Li, 2015). Therefore, this is a contribution to Chinese architecture, not to CAD (Li, 2015). To respond this, in addition to the clear statement of the values mentioned at the beginning of this thesis, as well as the discussions made in the three case studies chapters, more supportive discussion is drawn as follows. Considering the initial interest, Li is a software developer and currently develops new techniques using computer algorithms, for example, the *interpreter* based on Rhino (Li, 2014). And his long term ambition is to make a development environment based on this (Li, 2014). In this sense, what he means is that the novel work in this research project is not in writing new computer software based on Chinese architecture. However, this does not mean that there is no novel contribution to CAAD. This research work uses techniques that can be described as software “authoring” rather than “writing”. Equally, what is contributing and novel is the reflections on the comparison between parametric (authoring) approaches and shape grammar (writing) approaches to addressing the issue of studying architectural design rules. This research does not only look at traditional Chinese design rules and explore their applications in modern architecture. This research also uses contemporary parametric techniques to devise “scripts” that capture the rules in an authoring environment which can then be used to generate an infinite range of possible solutions. And this could also be further developed to form a database or a design tool as a long term ambition. This goes well beyond what the users could have done if they had been limited to manual techniques. For this reason CAAD is an essential ingredient and therefore this project has made a contribution to research that has CAAD as a key element.

Apart from these aspects, the Shape Grammar approach provides a good foundation that when studying the geometries prior to the modelling process. Due to its feature, the architectural geometries are well clarified in the generation of the grammars. To carry out the algorithm in parametrics, this is an important preparation. Especially when facing the complex structures without knowing the starting point, such as stated in Chapter 4 of the section case study, the Shape Grammar approach is the important reference and inspiration.

Accordingly, three major similarities between Shape Grammar and parametrics can be drawn. Both of them are derived systematically and logically; both of them are generative and productive; both of them can be symbolically and graphically illustrated. In contrast, three key differences can be identified as well. The parameters in the parametric method can be any variables, abstract or concrete, without the limitation of just geometrical entities. The rules used in parametrics can be any logic relationships, not only repetitions and the final outcome could involve many different variations.

8.2 Comparison with conventional interpretation

Andrew Li also criticizes that this research makes more sense as a contributions to the pedagogy of Chinese architectural history in terms of how and why CAD tools make learning easier and more effective (Li, 2015). In this case the research is addressing a different audience with different concerns: people who teach Chinese architectural history. He argues that if this is the case, “you need to speak their language, which does not include any technical CAD ideas since this makes it very difficult to explain CAD approaches to historians; I know, because I have tried” (Li, 2015). In a very long time, this opinion is strongly debateable. In addition, the issue mentioned by Li is not only reflected on the study between CAAD and Chinese architecture, but in general lies in all the studies between CAAD and historical architecture. In other words, the issue is whether architectural historians (or in general, architects and students) could accept CAAD techniques in approaching to the historical architecture studies. This is a very subjective topic. Therefore the discussion also takes the subjective experience into consideration.

In some respects, Li is correct. There was a conference “New Approaches in Chinese Garden History” (18th – 19th June 2015, in University of Sheffield, UK) which leaves the author the same impression as Li. The people attended were all architectural historians, some from landscape and some from architecture. The author discussed with researchers who all currently guide Chinese PhD students on topics of traditional Chinese garden or architecture studies. One gave an interesting view that he tried to avoid mentioning “style” and refused to use “pattern”. Another one doing research on *Yamen* (meaning government office, a traditional Chinese courtyard type house used in ancient dynasties) did not accept “rule” and never heard about the two rulebooks, which was completely different from the ideas presented in this research. Further, he presented the courtyard type house mainly by “orientation” rather than “rule”, although he accepted the central axis and symmetric feature (Jones, 2015). When mentioning a CAAD approach to such topics, they did not accept this at all, and seemed the CAAD explanation was not understandable to them. The same opinion was also held by their PhD students. This is a typical view held by some researchers outside the CAAD field, which is useful and worth taking into consideration, although different from those inside this field.

On the other hand, Li is not completely correct. As shown in Chapter 7, the master’s programme student Qu did his final project (Qu, 2014) on the topic of using a parametric technique to design traditional Chinese architecture. During that process, everything went well from learning basic parametric skills to applying rules on new design ideas. In a few months’ time, he progressed from a beginner to a good level. Apart from him, quite a number of students shows strong interest in using digital techniques on historical architecture studies, not only limited on Chinese architecture. Although some of them finally give up due to the technical difficulties, they do not have problem in understanding this concept and methodology. It could be presumed

that if they are given a longer time to practise the skills in order to overcome the technical difficulties, this concept and methodology would be valid for them. Similarly, when talking about experience in using virtual models to teach traditional Chinese wood construction and Shape Grammar approach in *Ying Zao Fa Shi* project, Li once mentions, “our students were surprisingly enthusiastic and even took pride in the sophistication of this uniquely Chinese construction system” (Li & Tsou, 1996). And students’ comments show they are truly enthusiastic about this approach (Li, 1997).

Although the topic discussed above is subjective, as a researcher, one must have a mature and reflective understanding of the field, and the different views within the field. Even the examples given above are limited and targets are relatively random, there are three key points can be summarized.

Firstly, since this research is at the intersection of two fields, there are different approaches towards a particular question based on different priorities and perspectives. For researchers working in the mainstream of their fields, this is usually straight forward. To provide a well-informed reflection on this debateable topic, understanding should be based on the fact that this is an area which can be approached in different ways. There is no absolute correct or incorrect answer. The research presented here takes one particular approach, which is valid and accepted by some people, although may not accepted by everyone. Meanwhile, the other side of the coin is, there are others would not take this approach and have a different view on how the field should be addressed. Additionally, the debatability leaves space for future research.

Secondly, the researcher mentioned in the first example having a different view and approach are mainly historians usually using conventional method of approaching historical architecture. They are probably people who are not technically strong and do not use advanced software. It is out of the scope of their normal way of working. But to make a novel contribution to knowledge, traditional ideas and conventional approaches may be challenged. If they are good researchers they should be open to the fact that those approaching the study from a different direction might also add valuable insights. Nevertheless, in the second example, the CAAD approach is highly accepted by those students. And they have some common features. They are students who are still learning, with few stable habits (certain way of thinking and working) and open to new techniques. They are also familiar with software. For those succeed in their projects, they have good scientific background and are strong either in logic algorithm or in programming to overcome the technical difficulties. Consequently, the debatability does not mainly lie in the approach itself, but lies in the background of the users. With the fulfilment of the pre-requisite, this approach is valid. Apart from these, Chinese are traditionally (in contemporary period) strong in mathematics, and in the current world are still pre-eminent in fields of mathematics and computer science. In this sense, to approach Chinese architecture by digital techniques is a good attempt. Differently, in ancient period, Chinese people never

formally studied mathematics or science, although a few talented people were good at it. This makes it interesting to reflect on how those writing the ancient rulebooks might have used computers if they had them. From what they passed on, to look at traditional Chinese architecture, a fundamental core of how the designs are derived is through mathematical rules.

Thirdly, architecture is continually developing, as are design and research methods. From the prehistoric requirement of shelters and protection to the medieval exhibition of power and religion, from the Renaissance's pursuit of beauty and aesthetics to the industrial age's intrinsic refinement of steel-frame, architectural design and research experienced the evolution from paper and pencil to computer and machine, from experience to specialty. Different from years ago, software based environment is a major trend for professionals in both practice and academia. And new techniques will be gradually accepted. This provides reassurance of the value of this research.

Chapter 9 Conclusion

The research presented here investigates to what extent traditional Chinese architecture can be reinterpreted using a variety of digital techniques based on the ancient rulebooks. Throughout this research, the understanding of the design concept, structure and guiding principles behind traditional Chinese architecture and the applicability of computational techniques to this style is enhanced. The involvement includes the exploration of the algorithmic representations of the rules, as well as building digital models and digitally fabricated model, and the evaluation from the applications of the research findings. This is a foundation of the longer term ambition to develop a powerful digital tool to assist the restoration or recreation of damaged or destroyed traditional architecture, as well as the generation of the new designs respecting traditional styles with such a digital environment.

When combining the three case studies in the parametric generation of the floor plan, section and the joint, it is found that the characters summarized from deriving the floor plans are consistent with those from generating sections, as well as the modelling of the joint. Taking Andrew Li's series of work of shape grammar approach to the traditional Chinese architecture into consideration, it can be concluded that traditional Chinese architecture has parametric characteristics. Since the whole structure of traditional buildings constructed using the rulebooks is complex and closely interrelated, a parametric method has the advantage of illustrating and generating the principles from the rulebooks to complex digital reconstructions. Also, it is proved that *Ying Zao Fa Shi* consisted of "formulas based on principles and proportions (Liang, 1984, p. 358)" through the digital modelling process. It is a parametric method that illustrates these formulas, which in this research is the relationships based on the principles and proportions in the rulebooks. The abstract "formulas" were then demonstrated by the concrete graphic models. Parametrics for the attempts of traditional Chinese architecture deal with the ancient information with the latest tool that derives from computational intelligence, which is a novel strategy to inherit and develop such ancient sophisticated heritage. The application is not limited to the restoration of ancient buildings, but could also be used as inspiration in the generation of new designs.

In the following sections of this chapter, responses to the aims and objectives set out in the introductory chapter will be given as a summary of the research. After this, the limitations and scope of the research will be discussed to recognise where there is potential for further research. Then the contribution to knowledge will be demonstrated. Finally, recommendations for future work will be suggested based on the above discussions.

9.1 Response to aims and objectives

The first objective was to rationally understand and analyse the current situation of Chinese architecture both in research and in practice, and then based on this propose proper and effective research scope and target. This was explored in Chapter 1 by reviewing the history of Chinese architecture, as well as the building distributions and their types and forms. Since Chinese architecture develops continuously, careful selection must be made such that the research targets must be typical and symbolic. And meanwhile, the scope cannot be too broad or infeasible. Together with the analysis on the current status of research and design practice, it is sensible to trace back to the real tradition with explicit record of the design concepts.

Once the research scope was outlined to meet the first objective, the second objective could be carried out. The work here, which formed the first part of Chapter 2, was to systematically review and document historical literature and analyse relevant research materials. The only two existing ancient literatures—*Ying Zao Fa Shi* and *Gongcheng Zuofa Zeli* were selected as the rules books and primary reference of this research. The understanding of the rules and regulations of the ancient design principles were focused on in order to summarize the features of the traditional style. Liang's research work played an important role in unfolding the ancient rulebooks. Based on the experience in the previous research carried out by historians, decision was made that *Ying Zao Fa Shi* would be used as a core and *Gongcheng Zuofa Zeli* together with the extant heritages would be the complement. The work here was also the basis for transforming the ancient rules into the algorithmic rules, and in turn, the basis of digital modelling, in the later case studies.

After the second objective was achieved, the third objective was carried out by reviewing previous research on the use of digital techniques as an analysis or presentation technique in relation to heritage studies, as well as those studies on Chinese architecture in relation to CAD environment or algorithmic representation. Reviews include conventional approach and Shape Grammar approach to *Ying Zao Fa Shi*, pattern language and a comparison between Chinese and Western architecture, and the research of proportion on traditional Chinese architecture. Apart from this, three recent projects were discussed: the digital representation of the Yuanming Palace, the digital fabrication of the Japanese joint and the parametric approach to *Gulou*. This process was necessary prior to the selection and experiment of the proper digital techniques. It also clarifies what has already been achieved in this field and what was missing.

Having studied the research context to meet the second and third objectives, the fourth objective was to develop a consistent and systematic process to digitally represent three important elements in traditional Chinese architecture. The three case studies formed Chapter 3, Chapter 4 and Chapter 5. The concept of *Cai* was throughout all the case studies and it was the key essence of *Ying Zao Fa Shi*. In each

case study, a description was made first and then an algorithm was derived. After these a series of attempts were carried out to achieve the optimizations. At the end of each case study, a discussion was made on both advantages and disadvantages observed in the process, and based on this, conclusion and future work suggestions were provided. The three case studies together built up a framework on how to digitally present traditional Chinese architecture including its overall proportion and the detailed joint element, which formed Chapter 6. Upon the completion of this objective, the possibility and limitation of digital techniques on such target were also examined; difficulties during the process were learnt and suggestions were raised.

The fifth objective was to provide contemporary designs that respects traditional values guided by the research findings, and also spreads the findings in education. Three applications were demonstrated. The set of parametrically generated designs of the rule based floor plan was an example of applying the research outcomes to inspire new design options. And through this, the implications and limitations of the research in traditional rules and digital techniques were reviewed and further understood. The design project done by the master's degree student showed the possibility of how to utilize this research to benefit architectural education and a wider audience. The practical project of the Chinese garden indicated the potential of suggesting architects and designers alternative options in designing traditional Chinese architecture other than conventional ways.

The final objective was to discuss and analyses the case studies and applications carried out and make key conclusions, following which comparisons of the key features of different approaches were given in order to obtain a rational and complete reflection to the research field. This was achieved in Chapter 8, where subjective and strongly debateable topics were opened and evaluated.

9.2 Limitations

There are some limitations which need to be acknowledged in order to clarify the scope of this research, which in turn can be the aspects for future research work. First, the nature of the case studies means that only selected elements of architecture with typical situations can be investigated. *Ying Zao Fa Shi* is considered as one of the greatest architectural literatures over a thousand years, containing a very rich information source of traditional Chinese architecture. This research makes a minor progress in understanding its essential concepts in the carpentry volume. Since it has been re-found in 1919, there is still a long way to go to fully unfold it. And based on this point, the second limitation is, the traditional Chinese style phrased in this research means the style mainly recorded in *Ying Zao Fa Shi*. People may argue that traditional Chinese style is a wide concept which far beyond *Ying Zao Fa Shi*. But over years, no explicit and complete definition exists. To avoid ambiguity in research,

the relatively narrow but clear meaning is utilized here. Again, to build up the full system of traditional Chinese architecture, much more work is needed. Third, *Gongcheng Zuofa Zeli* is treated as a complement to *Ying Zao Fa Shi* in this research rather than equally important. This is due to the impracticality of following both rulebooks in the algorithm and modelling process. But as introduced in many chapters, there are certain relationships between the Song style and Qing style buildings. Therefore, the focus of *Gongcheng Zuofa Zeli* could be a carry on research parallel to this one. Fourth, the design concepts included in *Ying Zao Fa Shi*, such as the concept of *Cai*, not only having architectural and cultural meanings, but also contains engineering and constructional reasons integrated within. To fully understand these design concepts, the engineering perspectives cannot be neglected. Fifth, the work presented in this research relies on the historical information and various interpretations to such information. The archaeological and historical findings are updated from time to time, as well as people's interpretations. Therefore, the digital representations will be updated accordingly. Last but not least, this research investigate both areas of computer aided architectural design and history of architecture, which brings benefits to both digital and architectural historical research. But meanwhile this limits the depth in both areas compared to those primarily concentrate on only one area. However, to bridge the gap and build up the link between the two areas is the trend for future research.

9.3 Contribution to knowledge

The research makes a contribution to knowledge in demonstrating how contemporary digital techniques can be applied to uncover lost, unclear or fragment ancient information and in turn to advance knowledge and understanding of significant Chinese architectural styles, especially under the situation that few heritage buildings are left, as well as there is a lack of systematic and complete records. Consequently, this enhanced understanding can then be used to rediscover, restore, refurbish and recreate the traditional Chinese architecture. This is achieved by turning descriptions and definitions into rules and algorithmic representations through the study of the rulebooks and the process of digital modelling. Although there are previous research on the topic of Chinese architectural history, the contribution of this research differs in two aspects. First, the work presented here solves the problems that historical materials cannot provide answers to, such as the ambiguities or the lost information. So this can be used as complementary to the ancient literature and heritage sites. Second, the digital techniques utilized in this research are internationally standard and understandable to a wide audience and architects, which avoid the limitation of the prerequisite of profound background in Chinese architecture and Chinese culture that conventional presentation usually requires.

The research also makes a contribution to knowledge in illustrating how digital computational techniques, especially parametrics, can be applied to a novel target, traditional Chinese architecture, which is different from the common area of complicated shapes of contemporary architecture that they are usually applied to. Although there are previous research on digital representation of various architectural styles, this research differs in three aspects. First, this research brings new inspirations to the contemporary digital techniques by integrating the cultural aspects, Chinese history, ancient politics, Chinese traditions and styles into the modelling process. Second, in the process of constructing the digital representations, the method of dealing with inconsistencies across unclear information and transforming the rules created by ancient people into the rules used in programming of machine language is well studied. Third, when combining the above two contributions, a direction of how to develop the current digital tools into a powerful interface that fitting the design of traditional Chinese architecture is suggested. Consequently, this research extends the function of digital techniques and bridges the gap between the traditional Chinese architecture and contemporary parametrics.

Therefore, the thesis can be considered an original contribution to both areas of architectural research; firstly in Computer Aided Architectural Design and research and secondly in the field of the history of Chinese architecture.

9.4 Future work suggestions

At the end of each case study, relevant recommendations of future work have been suggested especially for the corresponding contents, and they will not be repeated. Here suggestions will be made at a macro and general level.

First, as an extension of the floor plan case study, apart from individual buildings, based on the floor plan logic diagram, a similar parametric method can be used in generation of certain city plans, since several Chinese ancient cities also show parametric characteristics.

Second, the elevation, as another important element in traditional Chinese architecture, could be further researched. And in turn, the relationship between the floor plan and the elevation, as well as the section and the elevation, can be further studied.

Third, the complex structure joint, *dou gong*, has a large potential to be investigated. Related future works could include:

Comparing the wood and paper densities and other inner characterises to further investigate the possibility of using paper material instead of wood in practise.

If the above point could be achieved, the development of a recycled paper building in a traditional Chinese style could be a direction of new design.

Because paper expands with increased humidity, waterproofing mechanisms in the joint is a follow-up research area, and similarly for fire resistance, but environmentally friendly chemicals are available already to do this.

The mechanical performance of the paper joint should also be further studied.

What is more important, with the latest development of four dimensional printing technology, the joint could be a prospective research target. In addition to the tradition 3D concept, a fourth dimension of time is added into the printing technology which allows the outcome product has a flexibility to change its shape (as a response) under certain condition or environment, in order to fulfil some new functions that fit the new environment. The *dou gong* is a potential research target because under the earthquake condition, the vibrational waves will be the “changing condition or environment”, while the flexibility of self-adjustment of the shape and inter relationships between all the components could be studied as a respond, in order to continuously fulfil the anti-earthquake requirement, which is the most unique and significant function of *dou gong*.

Fourth, more cultural and functional related aspects, such as *feng shui* (wind and water), orientation of the traditional buildings, and Chinese garden patterns and layouts, can be explored to enhance the understanding from this research.

Fifth, the add-ons to the software Grasshopper and Rhino could be further developed into a more user friendly interface based on the features of traditional Chinese architecture in order to broaden the application which fits the different design demand.

The final recommendation is to use the research outcomes presented here as an educational tool to introduce traditional Chinese architecture to a wider international audience by the method of digital representation. This can further raise attention to this field outside China and emphasis the importance that traditional Chinese architecture contributes to the world architecture. And meanwhile inside China, encourage young generations to re-discover and appreciate the traditional values, as well as reflect how modern architecture in China can be genuinely Chinese in origin rather than international.

References

Publications

Alexander, C., 1977. *A pattern language: towns, buildings, construction*. 2nd ed. New York: Oxford University Press.

Anon., 1734. *Gongcheng Zuofa Zeli (Structural Regulations)*. s.l.:s.n.

Anon., 2015. Unveiling a New Chinatown. *My planet Liverpool*, Volume 19, pp. 55-57.

Bao, D., n.d. *A hand painting of the Forbidden City*. Beijing: China Intercontinental Press.

Bao, R., 2013. *Study on the logical building process based on programming*. Beijing: CaDesign.cn.

Bhatt, R., 2010. Christopher Alexander's pattern language: an alternative exploration of space-making practices. *Journal of Architecture*, Volume 15 Issue 6, pp. 711-729.

Boerschmann, E., 1911. *Die Baukunst und religiöse Kultur der Chinesen*. Berlin: s.n.

Brown, A. & Knight, M., 1995. An Integrated Hypermedia Project. *Multimedia and Architectural Disciplines European Conference on Education in Computer Aided Architectural Design in Europe*, 16-18 November, p. 111.

Burry, M., 2005. Digitally Sponsored Convergence of Design Education, Research and Practice. *Proceedings of the 11th International Conference on Computer Aided Architectural Design Futures*, 20-22 6, p. 3.

Chen, L., 2014. Hands of the Craftsmen, Mimicking the Hands of Heaven Records of the Rammed Earth Process for "the Mountain Residence by the Waterside". *Architectural Journal*, Volume 1, pp. 49-52.

Chen, M., 1993. *A study of structural carpentry in the Ying Zao Fa Shi*. Beijing: Wenwu Press.

Chiu, C. B., 1997. *Yuanye: le traite du jardin*. Besançon: Les Éditions de l'Imprimeur.

Di Mascio, D., 2014. *Perspective from S.E., rendering based on Mackintosh's earliest surviving drawings of January 1904 and showing his specification for pale yellow Dullatur sandstone*. [Art] (Mackintosh Architecture, University of Glasgow).

Di Mascio, D., 2015. *Scotland Street School* [Interview] (2 7 2015).

Fairbank, W., 1985. Liang Ssu-ch'eng: A Profile. In: *A pictorial history of Chinese architecture: a study of the development of its structural system and the evolution of its types*. Cambridge, Mass: MIT Press.

-
- Feng, J., Fang, Z. & Petermann, S., 2014. Roof. In: J. Westcott, ed. *A series of 15 books accompanying the exhibition elements of architecture at the 2014 Venice Architecture Biennale*. Venice: s.n.
- Fu, X., Glahn, E., Thorp, R. L. & Juliano, A. L., 1984. *Chinese Traditional Architecture*. New York: Metropolitan Printing Company.
- Gips, J., 1975. *Shape Grammars and their Uses*. Basel: Birkhauser.
- Gisbert, C., 1907. *Sepultures imperiales de la Chine*. Bruxelles: s.n.
- Guo, D. & He, Y., 2012. *Digital representation of Yuanming Palace*. Shanghai: Western Shanghai Book Co. Ltd..
- Hardie, A., 1988. *Craft of Gardens*. Yale : Yale University Press.
- Hardie, A., 1988. *Craft of Gardens*. New Haven & London: Yale University Press.
- International Stadtbau Atelier, n.d. *Urban Renewal of a Historic District Fashi Village and Stone Street*, Quanzhou: s.n.
- Ito, C., 1903. *Shinkoku hokkyo shikinjo temmon no kenchiku*, Tokyo: The Japanese investigation gave way to the publication.
- Jabi, W., 2013. *Parametric Design for Architecture*. London: Laurence King Publishing Ltd.
- Ji, C., 1631. *Yuan Ye*. s.l.:s.n.
- Jones, P. B., 2015. *The sense of direction in Imperial Chinese architecture*. Sheffield, s.n.
- Kanasaki, K. & Tanaka, H., 2013. Traditional Wood Joint System in Digital Fabrication. *31st eCAADe conference proceeding, 18-20 Sep 2013*, Volume 1, pp. 711-717.
- Li, A., 2001. *A shape grammar for teaching the architectural style of the Ying Zao Fa Shi*. Cambridge, Mass: MIT .
- Li, A., 2003. The Yingzao fashi in the information age. *The Beaus-Arts, Paul Philippe Cret, and Twentieth Century Architecture in China*, 3-5 10.
- Li, A., 2015. *Discussion on Shape Grammar and Parametric approach to Chinese architecture* [Interview] (1 4 2015).
- Liang, S., 1984. *The two "grammar books" of Chinese architecture*. Beijing: China Architectural Industry Press.
- Liang, S., 1983. *Ying Zao Fa Shi Zhu Shi (The annotated Ying Zao Fa Shi)*. Beijing: Architectural Industry Press.

-
- Liang, S., 1985. *A pictorial history of Chinese architecture: a study of the development of its structural system and the evolution of its types*. Cambridge, Mass: MIT Press.
- Liang, S., 2001. *The Collected Edition of Liang Sicheng*. Beijing: China Architectural Industry Press.
- Liang, S., 2006. *Analysis on Gongcheng Zuofa Zeli (Structural Regulations) from Qing Dynasty*. Beijing: Tsinghua University Press.
- Liang, S., 2006. *Qing Shi Ying Zao Ze Li (Qing Style Building Regulation)*. Beijing: Tsinghua University Press.
- Li, A. & Tsou, J.-Y., 1996. Using Virtual Models to Teach Traditional Chinese Wood Construction. In: T. Kvan, ed. *The Introduction of Technology: CAAD Teaching and Research Directions in Asia*. Hong Kong: University of Hong Kong, pp. 119-130.
- Li, D., Knight, M. & Brown, A., 2013. A Parametric Recreation of Traditional Chinese Architecture-- A case study on the floor plan. *Proceedings of the 31st eCAADe Conference, Delft University of Technology*, Volume 2, pp. 697-703.
- Li, J., 1103. *Ying Zao Fa Shi (营造法式)*. 2nd ed. s.l.:s.n.
- Li, J., 2006. *Ying Zao Fa Shi (营造法式)*. Beijing: China Bookstore (中国书店).
- Lin, S., 2013. The origin of timber structure of Penghu traditional temples. *The proceeding of the 10th academic conference of Penghu studies*, pp. 101-122.
- Liu, D., ed., 1984. *History of Chinese ancient architecture (中国古代建筑史)*. 2nd ed. Beijing: China Architectural Industry Press.
- Liu, D., 2009. *A standard of construction and craft in engineering for traditional style architecture*. Beijing: China Architectural Industry Press.
- Lo, Y.-N., 2010. Siheyuan and Hutongs: The Mass Destruction and Preservation of Beijing's Courtyard Houses. *AIArchitect*, Volume 17.
- Ma, B., 2003. *Chinese ancient architecture carpentry technology*. 2nd ed. Beijing: Science Press.
- Maver, T. & Petric, J., 1999. Virtual Heritage--Is there a future for the past?. *SIGRADI Conference Proceedings (September 29th - October 1st 1999)*, pp. 482-487.
- McAteer, 2011. *View from N.E..* [Art].
- Miao, P., 1990. The Essence of Tradition--Thirteen Characteristics of Chinese Traditional Architecture. *Journal of Building and Planning National Taiwan University*, Volume 5, No. 1, pp. 57-72.

-
- Mitchell, W., 1992. Computer-Aided Design Media: A comparative analysis. In: F. Penz, ed. *Computers in Architecture: Tools for design*. 1st ed. Essex: Longman Group UK Ltd, pp. 53-62.
- Office, 1904. *N. elevation, January 1904*. [Art] (Glasgow City Archives Collection).
- Pan, G., ed., 2009. *A history of Chinese architecture (中国建筑史)*. 6th ed. Beijing: China Architectural Industry Press.
- Pan, G. & He, J., 2005. *The explanation of Ying Zao Fa Shi*. Jiangsu, Nanjing: Southeast University Press.
- Peng, Y., 2011. *Analysis of the traditional Chinese garden*. Beijing: China architectural industry Press.
- Qu, Z., 2014. *Experiment of Exploring the Practical Usage of Parametric Rules-- An approach for Contemporary Chinese traditional architecture heritage*, UK: University of Liverpool.
- Sass, L., 2001. Reconstructing Palladio's Villas: A computational analysis of Palladio's villa design and construction process. *Proceeding of ACADIA 2001*, pp. 212-225.
- Shentu, T., Cheng, Y. & He, S., 2014. Collaboration of Architectural Design with Structural Design on Local Construction Outlook Retrospection and Reflection of Structural Design for the "Mountain Residence by Waterside". *Architectural Journal*, Volume 1, pp. 53-56.
- Stiny, G., 1980. Introduction to Shape and Shape Grammars. *Environment and Planning B7*.
- Tedeschi, A., 2011. *Parametric Architecture with Grasshopper:Primer*. Brienza: Le Penseur.
- Tian, Y., 2009. *The design of the pseudo-Chinese ancient architecture*. Beijing: Chemical industry Press.
- Wang, G., Liu, C. & Duan, Z., 2011. *Study of proportion and scale of Chinese ancient timber architecture*. Beijing: China architectural industry Press.
- Wang, G., Liu, C. & Duan, Z., 2011. *The research on proportion of Chinese ancient timber frame architecture*. Beijing: China Architectural Industry Press.
- Wang, H., 2013. *Paraphrase of Ying Zao Fa Shi*. Wuhan: Huazhong University of Science and Technology Press.
- Wang, S., 2014. Inquiring the Hills from beyond the Bank: An aggregation of diversified architectural typology. *Architectural Journal*, Volume 1, pp. 43-48.

-
- Webb, N. & Brown, A., 2011. Digital Forensics as a tool for augmenting historical architectural analysis. *Proceedings of CAADRIA 2011, Hong Kong*, pp. 505-515.
- Webb, N. J., 2012. *Digital re-analysis of lost or unbuilt architecture*, UK: University of Liverpool.
- Woodbury, R., 2010. *Elements of parametric design*. London and New York: Routledge.
- Wu, Q., 2005. Bracket teaching program: A shape grammar interpreter. *Automation in Construction*, Volume 14, pp. 716-723.
- Xiong , L., Xiong, W. & Zhang , H., 2013. Gulou Structure Grammar and its Computer Implementation-- A computational approach to preserve the ethnic building technique and to guide new designs. *Proceedings of eCAADe 2013*, Volume 2, pp. 725-733.
- Zhang , C. & Tang, F., 2011. Study on modern residential building under the influence of Chinese traditional thinking: Take Vanke Fifth Garden as an example. *Value Engineering*, Volume 1, p. 55.
- Zhang , S. & Sun, F., 2011. Chinese House Villa Design of Cathay View. *China Academy Journal*, pp. 133-137.
- Zhang, Z., n.d. *Qing Ming Shang He Tu (Along the river during the Qingming Festival)*. [Art].
- Zhu, J., 2006. To interpret tradition in vernacular Chinese: On Vanke's project of the fifth garden. *Time Architecture*, Volume 3, p. 20.
- Zou, Q., 2011. *Ying Zao Fa Shi (营造法式)*. Beijing: People's Publishing House.

Web References

Anon., 1997. *Song construction and the Yingzao fashi*. [Online]

Available at: http://andrew.li/yzfs/yzfs_new/b2.htm

[Accessed 19 7 2015].

Anon., 2009. *Designer builds up "bubble" for Hutong in Beijing*. [Online]

Available at: <http://discover.news.163.com/09/0915/09/5J8AMT99000125LI.html>

[Accessed 30 6 2015].

Anon., 2010. *Cathay View*. [Online]

Available at: <http://cathayview.cn/>

[Accessed 30 6 2015].

Anon., 2013. *The fake Paris town in Hangzhou becomes an empty town*. [Online]

Available at: <http://china.cankaoxiaoxi.com/2013/0810/253337.shtml>

[Accessed 30 6 2015].

Anon., 2013. *The old city wall of Beijing*. [Online]

Available at: http://blog.sina.com.cn/s/blog_627240870101dj4b.html

[Accessed 29 6 2015].

Anon., 2013. *Zhaozhou Bridge*. [Online]

Available at:

<http://zy.zwbk.org/index.php/%E8%B5%B5%E5%B7%9E%E6%A1%A5>

[Accessed 24 6 2015].

Anon., 2014. *M233 Scotland Street Public School*. [Online]

Available at: <http://www.mackintosh-architecture.gla.ac.uk/catalogue/browse/display/?rs=232&xml=des>

[Accessed 3 7 2015].

Anon., 2014. *Model of the Portfolio of the Leis in Qing Dynasty*. [Online]

Available at: <http://www.nipic.com/detail/huitu/20131228/214800764200.html>

[Accessed 27 6 2015].

Anon., 2014. *The demolition of old Beijing city walls in 1957*. [Online]

Available at:

http://www.21ccom.net/articles/history/minjian/20141031115536_all.html

[Accessed 29 6 2015].

Anon., 2015. *Currently extant magnificent Chinese ancient architecture*. [Online]

Available at:

http://mp.weixin.qq.com/s?__biz=MjM5MDEyNDE4MQ==&mid=208557183&idx=1&sn=a8c746fa5b9a6b5ffebd096a0d4577f8&scene=5#rd

[Accessed 24 6 2015].

-
- Anon., 2015. *Mount Wutai Fuoguang Temple Wenshu Hall*. [Online]
Available at: http://www.dianliwenmi.com/postimg_377349.html
[Accessed 18 11 2015].
- Asuni, 2015. *Visual ARQ*. [Online]
Available at: <http://www.visualarq.com/>
[Accessed 6 7 2015].
- Baidu, n.d. *Hutong Bubble*. [Online]
Available at: <http://baike.baidu.com/view/2822307.htm>
[Accessed 2 11 2015].
- Carollin, 2014. *Shishahai Hutong in Beijing*. [Online]
Available at: <http://home.gamer.com.tw/creationDetail.php?sn=2317091>
[Accessed 29 6 2015].
- Center for Environmental Structure , n.d. *Pattern Language*. [Online]
Available at: <http://www.patternlanguage.com/index.html>
[Accessed 13 8 2015].
- Guo, N., 2010. *Famous Chinese Architects*. [Online]
Available at:
http://tupian.baik.com/a4_68_87_01300000802987127711878116025_jpg.html
[Accessed 27 6 2015].
- Lee, B., 2014. [Online]
Available at: <http://leebapa.blog.163.com/blog/static/1109681382014195502247/>
[Accessed 17 6 2015].
- Li, A., 1997. *Building width and bay width*. [Online]
Available at: http://andrew.li/yzfs/yzfs_new/b11.htm
[Accessed 5 10 2015].
- Li, A., 1997. *Students' reaction (in the Ying Zao Fa Shi project)*. [Online]
Available at: <http://andrew.li/yzfs/yzfswebp/reaction.htm>
[Accessed 14 7 2015].
- Li, Q., 2009. *The investigation of the length of the Great Wall constructed in Ming Dynasty for the first time*. [Online]
Available at: <http://news.sciencenet.cn/htmlnews/2009/4/218450.html>
[Accessed 26 6 2015].
- Li, S., 2013. *Interview of Shu Wang: We cannot go back to the tradition, but it can be revived*. [Online]
Available at: http://www.chinapictorial.com.cn/ch/se/txt/2013-09/03/content_565236.htm
[Accessed 2 7 2015].

-
- Li, A., 2014. *The interpreter project*. [Online]
Available at: <http://andrew.li/interpreter/index.html>
[Accessed 12 7 2015].
- Liang, S., n.d. *Two text books of Chinese architecture*. [Online]
Available at: <http://gs.cclawnet.com/zhongguojianzhuyishu/20j022.htm>
[Accessed 4 8 2015].
- MAD Studio , 2006. *Hutong Bubble 32*. [Online]
Available at: <http://www.i-mad.com/work/hutong-bubble-32/?cid=55>
[Accessed 30 6 2015].
- MAD Studio, 2012. *Shan-shui City project*. [Online]
Available at: <http://tieba.baidu.com/p/2043745359>
[Accessed 6 10 2015].
- Mcor Technologies Ltd, 2015. *Matrix 300+*. [Online]
Available at: <http://mcortechnologies.com/3d-printers/matrix-300-plus/>
[Accessed 7 2 2016].
- Mimike, 2013. *Chinese architectural history*. [Online]
Available at: <http://mooc.guokr.com/note/1833/>
[Accessed 18 11 2015].
- Preece, R., 2012. *A little corner of England? No it's a Chinese knock-off! Architects in Shanghai create complete traditional village of mock Tudor homes, local pub and cobbled streets*. [Online]
Available at: <http://www.dailymail.co.uk/news/article-2185526/A-little-corner-England-No-Chinese-knock-Architects-Shanghai-create-traditional-village-mock-Tudor-homes-local-pub-cobbled-streets.html>
[Accessed 30 6 2015].
- Shi, J., 2015. *Refurbishment of the Forbidden City*. [Online]
Available at: <http://www.zuojiawang.com/yishu/11618.html>
[Accessed 27 6 2015].
- Sowa, C. A., 2005. *Review of Unbuilt America*. [Online]
Available at: <http://www.minervaclassics.com/unbuilt.htm>
[Accessed 6 7 2015].
- Stephen, 2007. *59edu*. [Online]
Available at: <http://www.59edu.com/Article/ShowArticle.asp?ArticleID=3778>
[Accessed 17 6 2015].
- Victor, A., 2014. *China creates its very own Venice, complete with man made canals, gondoliers and European-style buildings*. [Online]
Available at: http://www.dailymail.co.uk/travel/travel_news/article-2801750/China-

Appendix 1 Gherkin project in the 2015 Constructionarium

In the Gherkin project, a Gherkin with the scale of 1:25 to the real one was built up by a team of fifteen students in six days on site and several days preparation based on the ten informative drawings (drawings are provided by the Constructionarium site). In this project, all the activities were done by the participants; mainly included surveying, shuttering, concrete foundation work, steel work and assembly (see Figure 278 to Figure 281). During the process, apart from the constructional skills, participants mainly suffered from difficulties of parametric designed steel components in assembly. As the components were similar in shape, they were not easy to distinguish. And since they were closely inter link with each other, if one component was assembled to the wrong position, the rest parts would not work well. The solution was to review the original parametric design and found out the complex relationship between the components. This is not only the key feature in parametric design process, but also the essence in solving the problem in construction process.



Figure 278. Surveying for the foundation

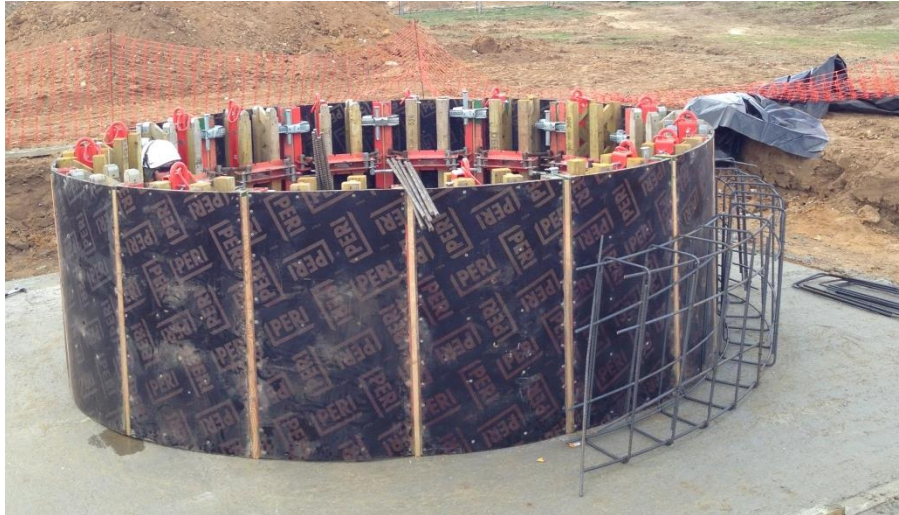


Figure 279. Shuttering for the foundation

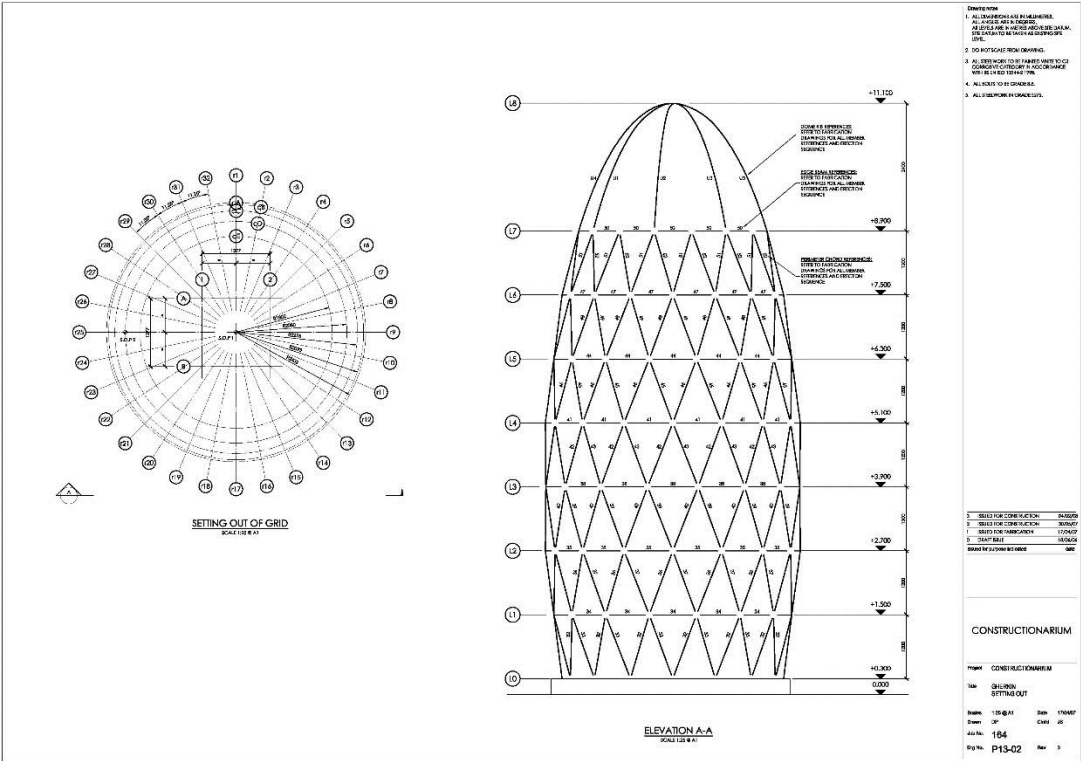
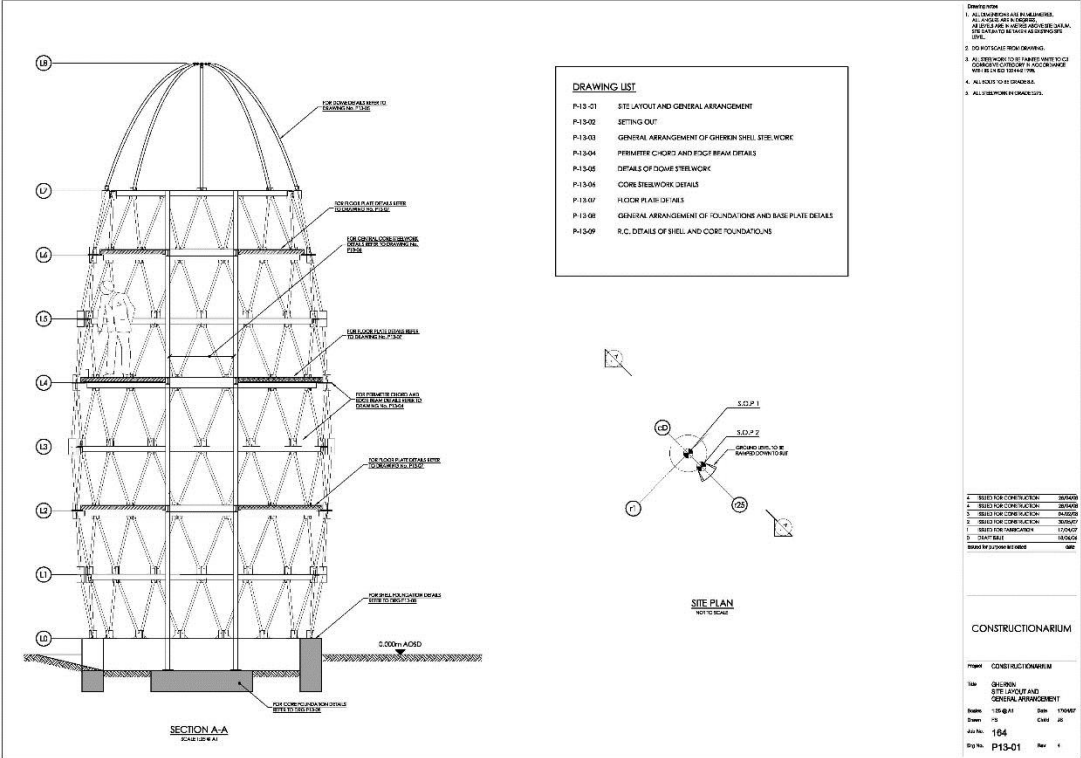


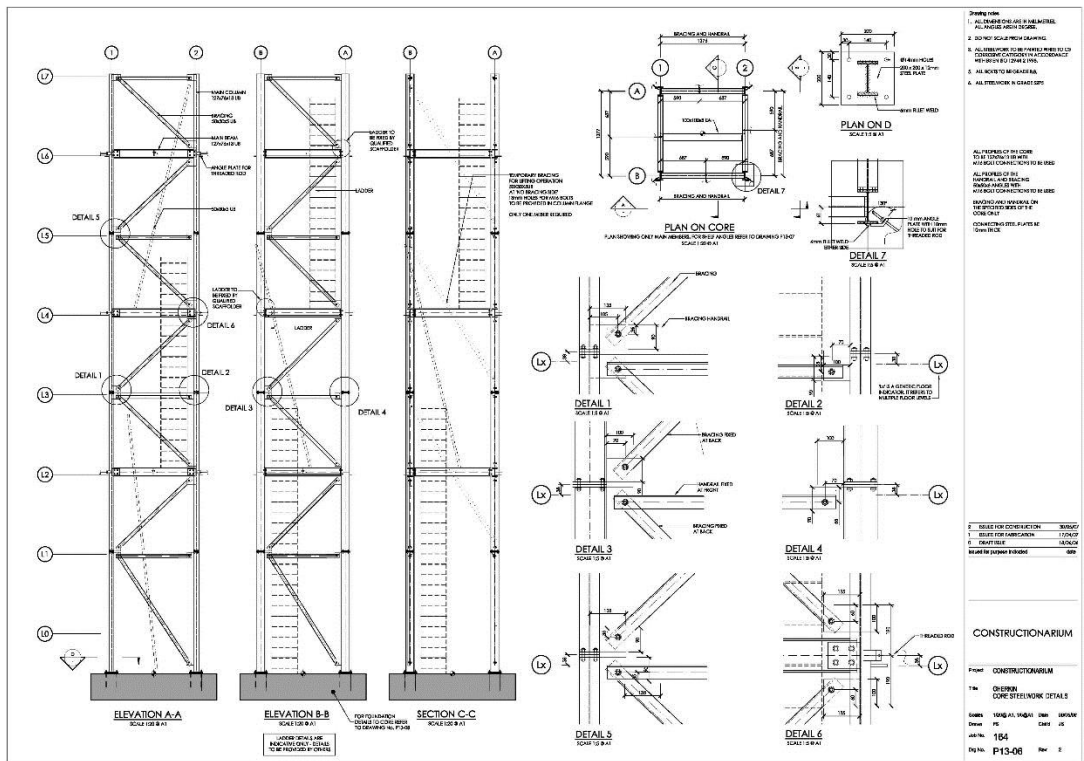
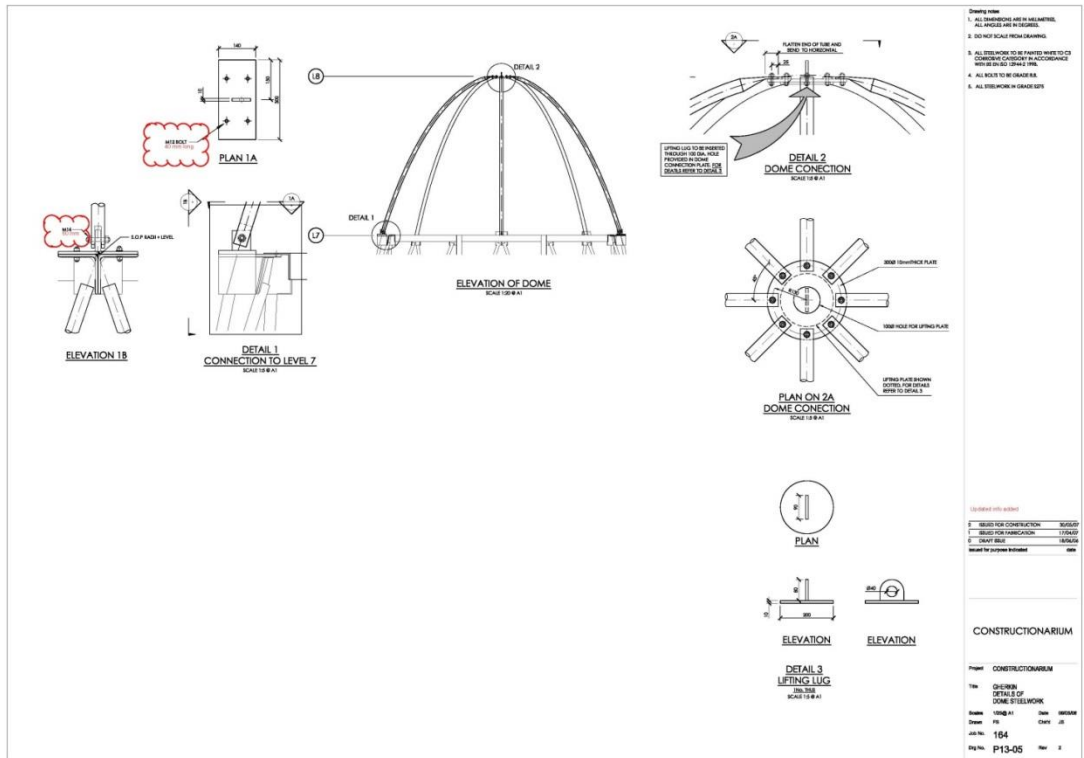
Figure 280. Concrete foundation work

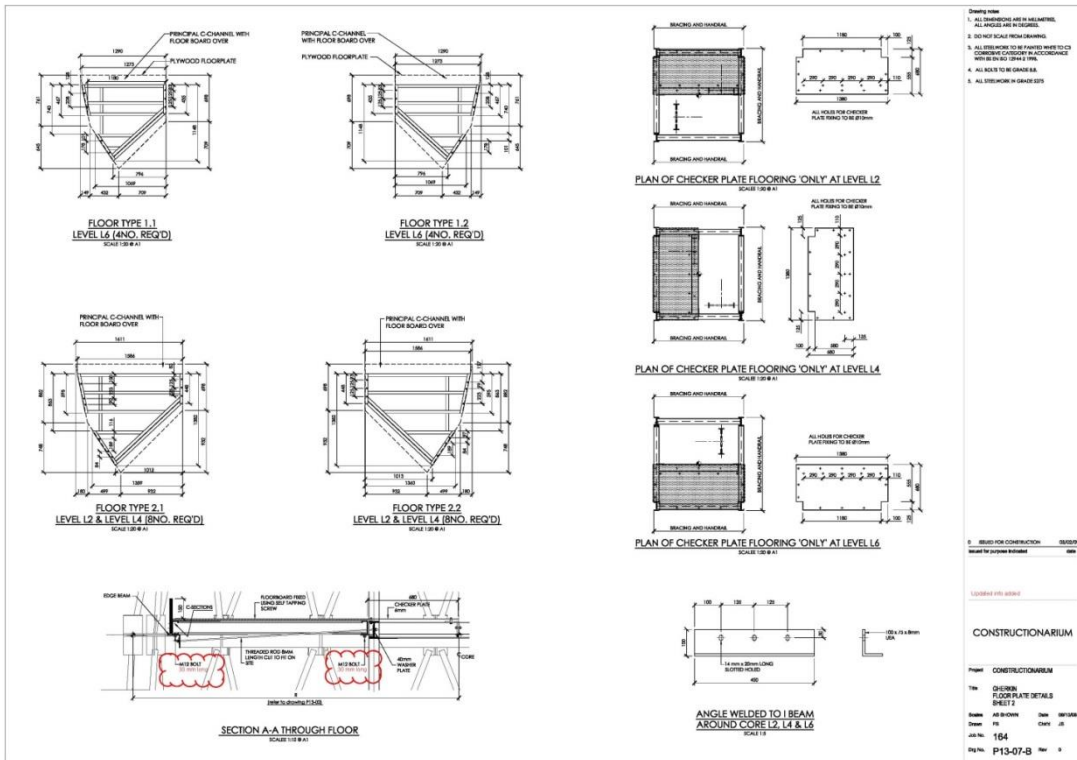
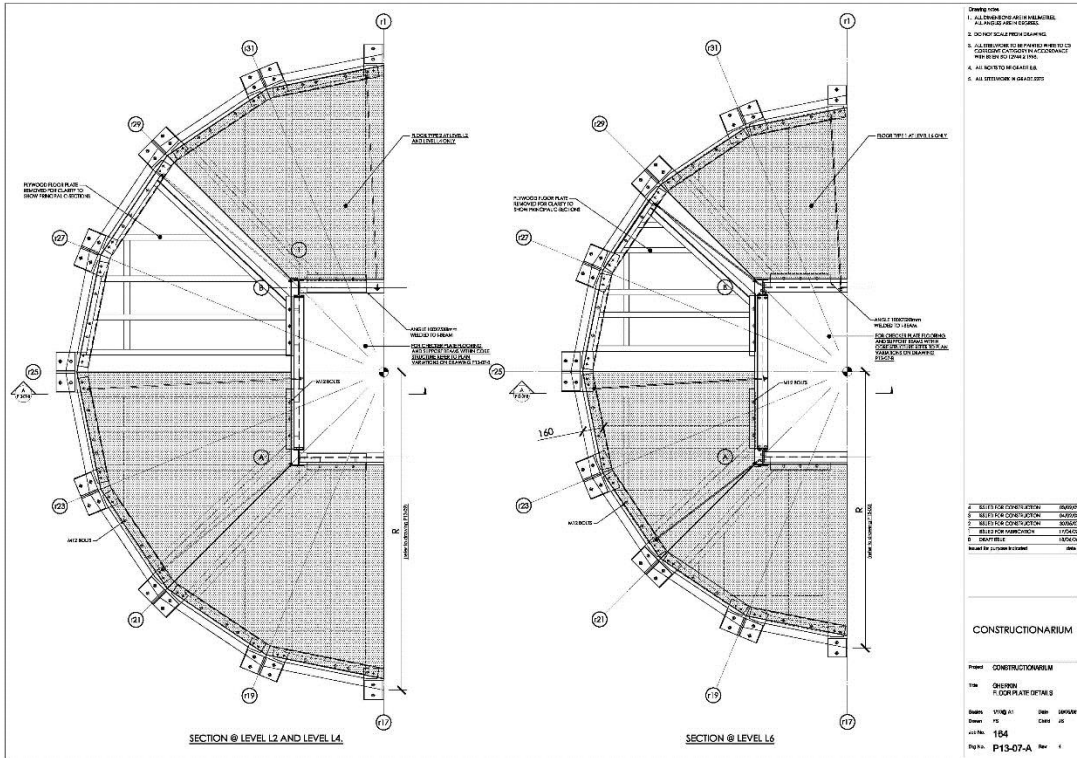


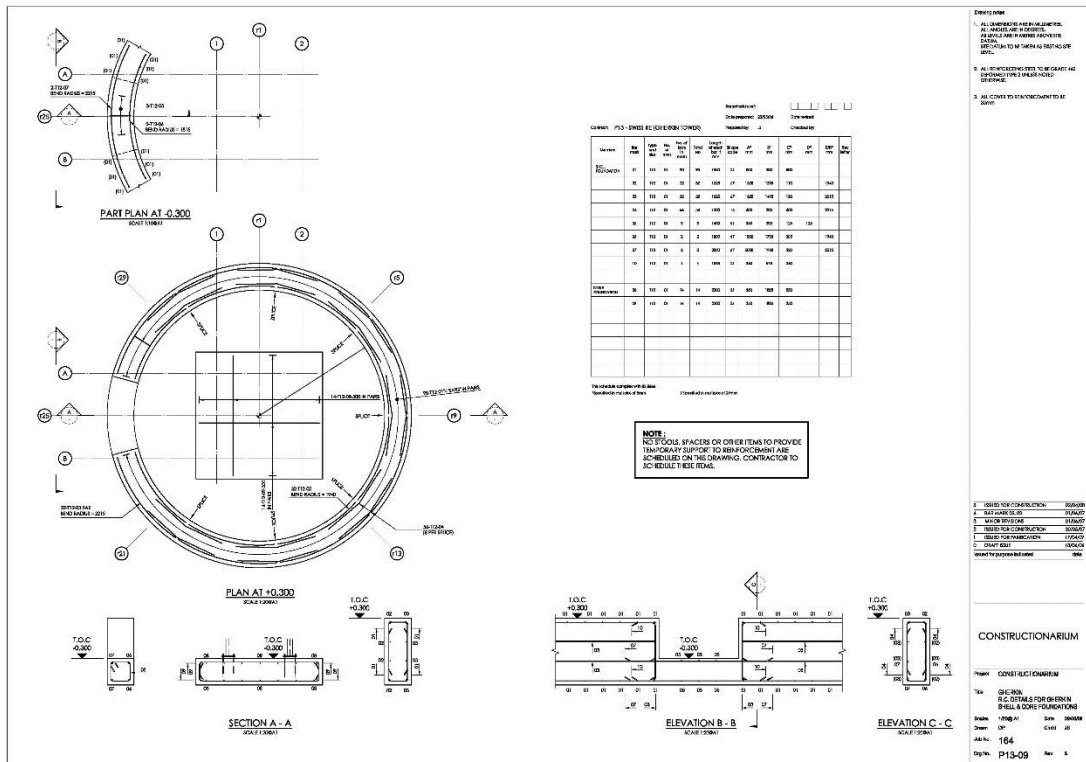
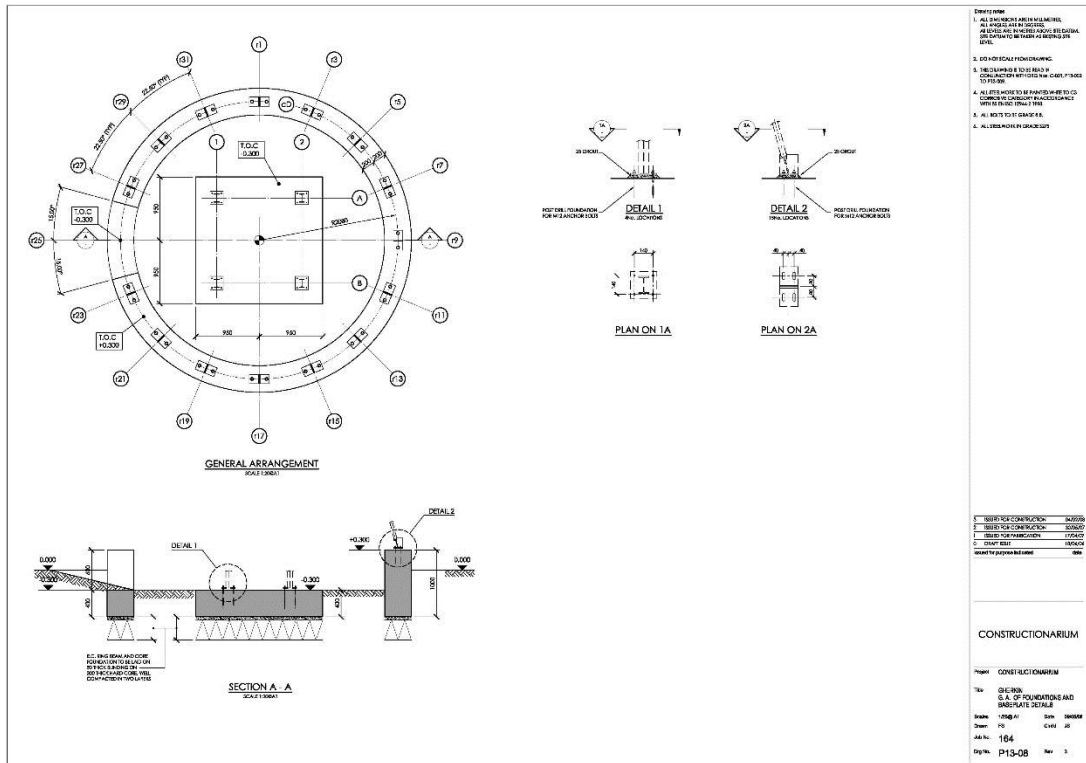
Figure 281. Steel work and assembly

The following ten drawings are the basic information for this project and were provided by the Constuctionarium site.









Appendix 2 The floor plan questionnaire and diagrams of the survey

Questionnaire:

Instruction: You will be presented with plan drawings of traditional Chinese buildings. Some of these drawings will be actual extant heritage buildings, and some may not. Please answer the questions to the best of your ability in relation to these drawings.

About yourself:

1. What is your gender?

Female, Male

2. What is your age?

Under 18, 18-24, 25-34, 35-50, Over 50

3. What is your professional background?

Architectural professional (fields include architecture, civil engineering, building service and management, etc)

Non architectural professional

4. What is your cultural background?

Chinese

Non-Chinese (familiar with Chinese architecture)

Non-Chinese (not familiar with Chinese architecture)

Questions for the diagrams:

1. To what extent do you agree the diagram presents a floor plan having the characteristics of traditional Chinese style?

Strongly agree, agree, not sure, disagree, strongly disagree

2. If you tend to agree, could you please specify the reasons for your decision?
(multiple choice)

Symmetric rectangular shape

Featured distribution of the bays (small units/areas)

The use of the column

The position of front and back gate, walls and plinth

Orientation of locating at the north and facing the south

Other (please specify)

3. If you tend to disagree or you are not sure, could you please specify your reason(s)?

4. To what extent do you think the diagram is a real extant building or a computer generated diagram (not real extant building)?

Definitely real, possibly real, not sure, possibly computer generated, definitely computer generated

Choose to answer either Q5 or Q6 or Q7 based on the answer to Q4

5. If you tend to think it is real, could you please specify the reasons for your decision? (multiple choice)

I have seen this one or similar ones before.

In my experience, it has the characteristics of a traditional Chinese style.

The diagram indicates a reasonable space for daily use.

The dimension and scale is consistent with the traditional Chinese buildings.

Other (please specify)

6. If you tend to think it is not real, could you please specify the reasons for your decision? (multiple choice)

I have never seen this before.

It looks different from those I have seen or known.

The diagram indicates an unreasonable space for daily use.

The dimension and scale is out of the boundary of traditional Chinese buildings.

Other (please specify)

7. If you are not sure whether the diagram is a real extant building or a computer generated diagram, could you please specify your reason(s).

Diagrams:

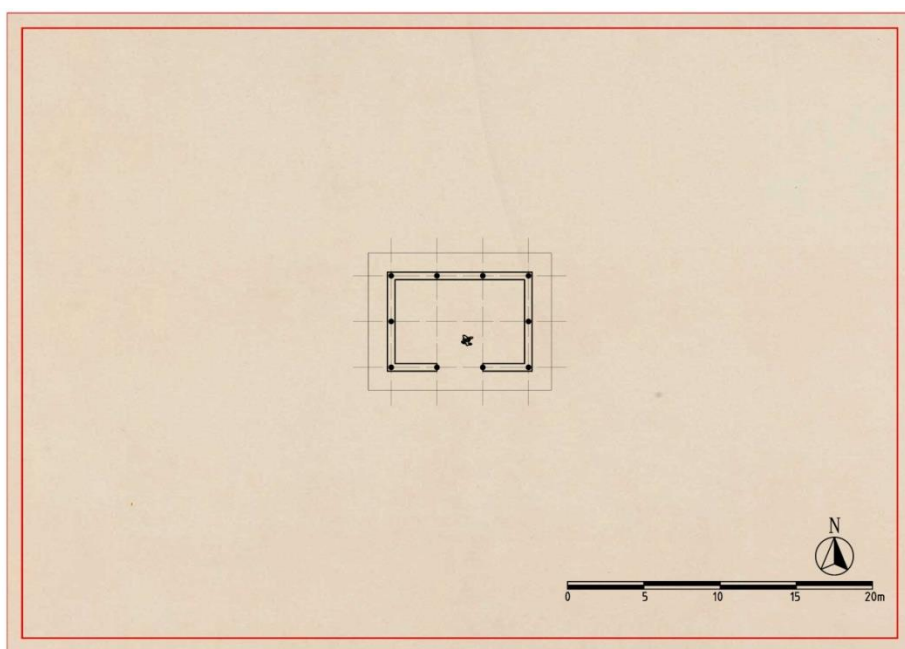


Figure 282. Computer generated 3-bay 2-rafter

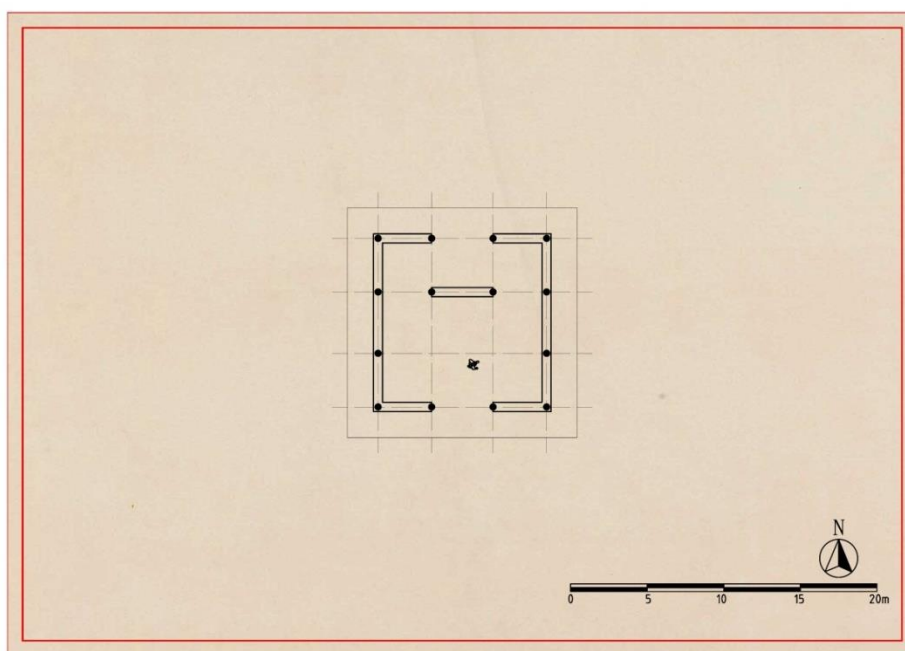


Figure 283. Qingliang temple middle hall

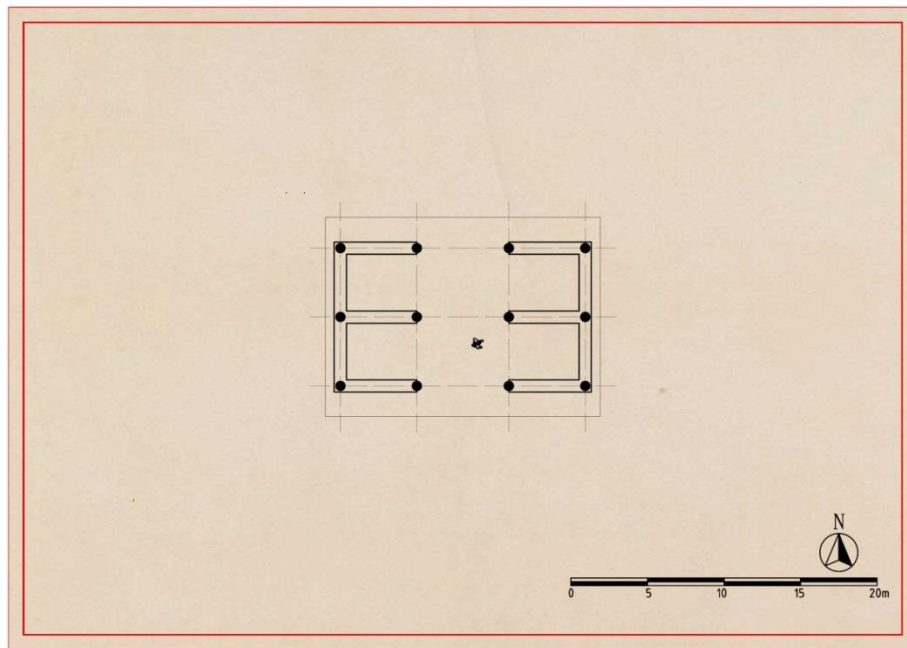


Figure 284. Gate of Dule temple

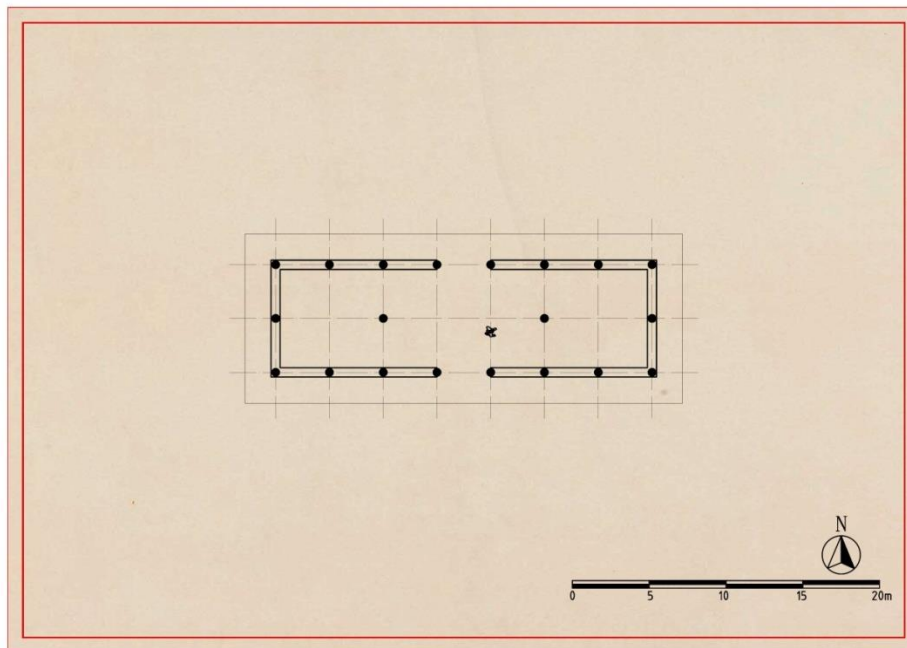


Figure 285. Computer generated 7-bay 2-rafter

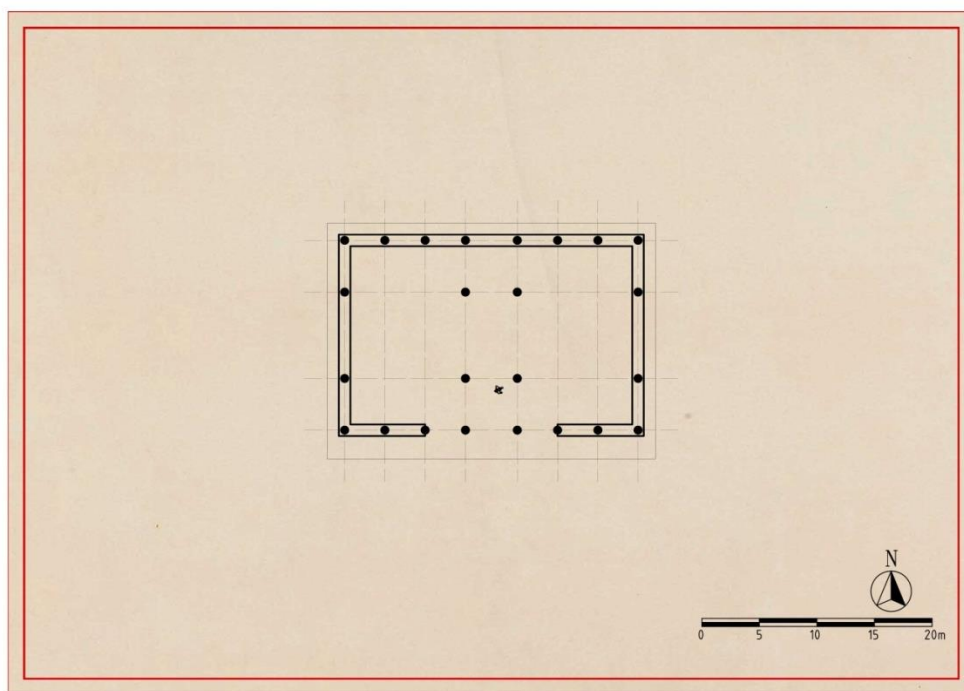


Figure 286. Guangshengxia temple major hall

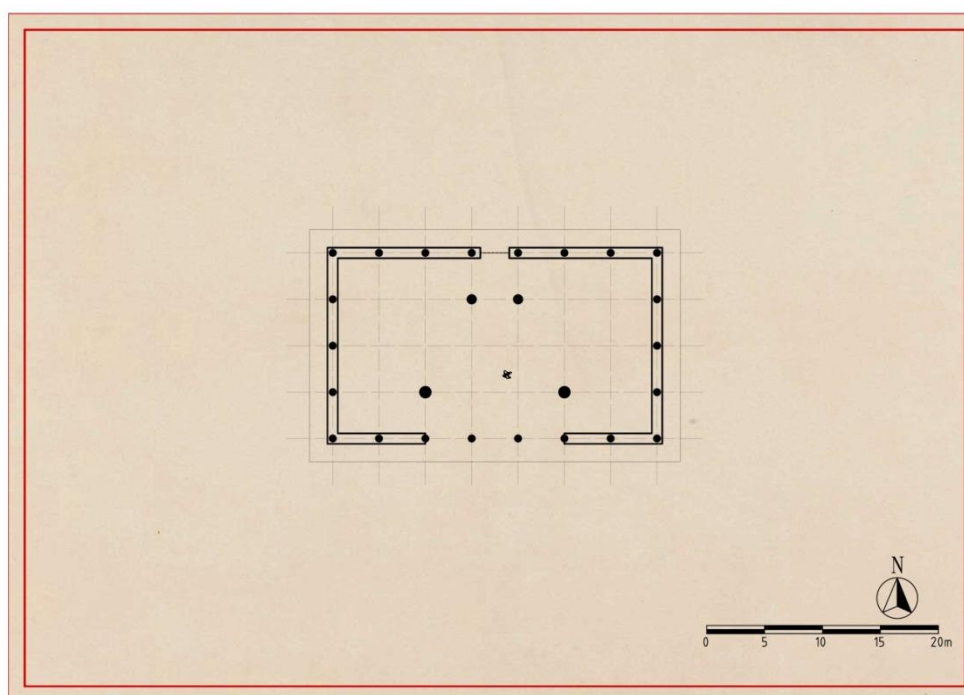


Figure 287. Foguang temple Wenshu hall

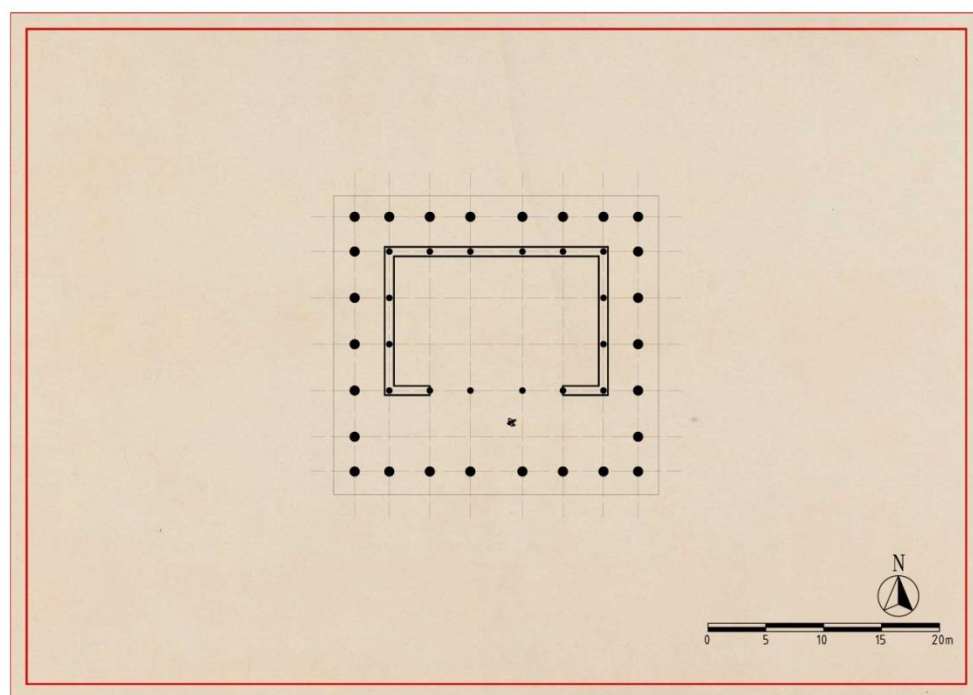


Figure 288. Jin ci Shengmu hall

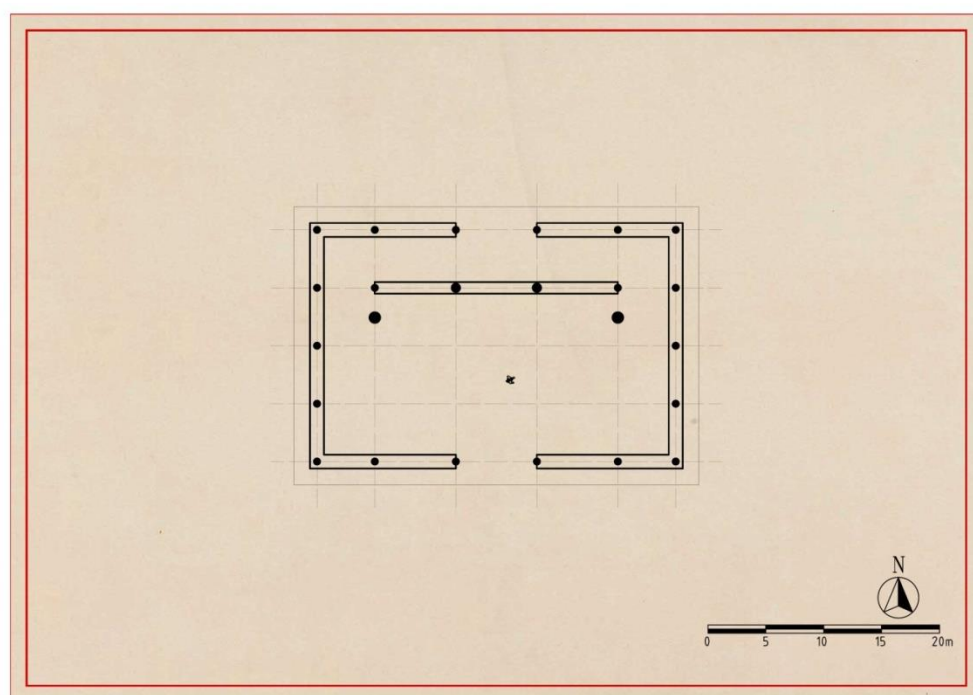


Figure 289. Shenhua temple san sheng hall

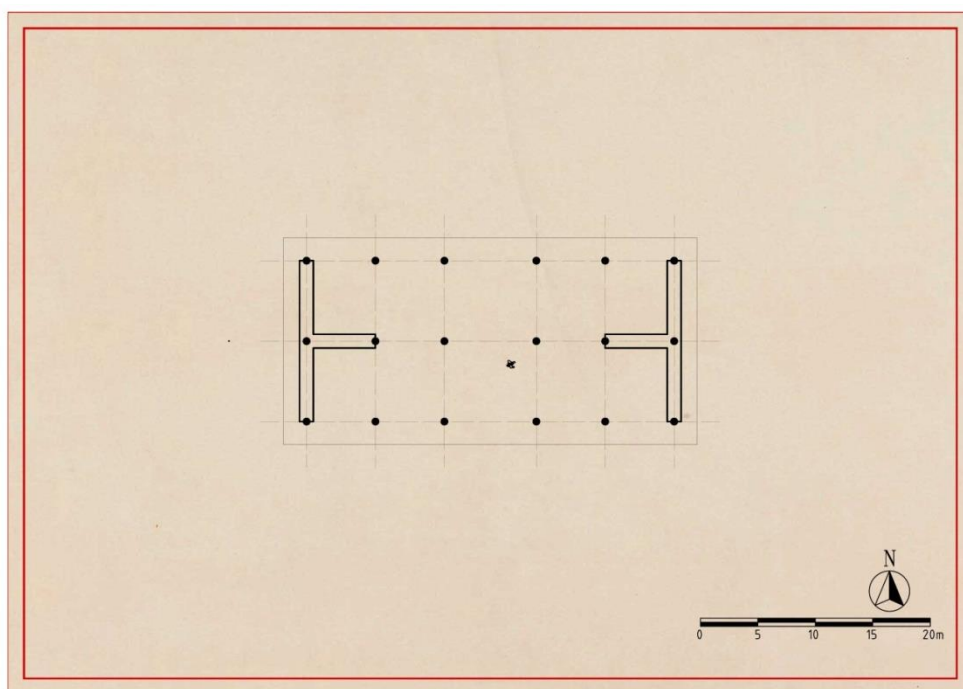


Figure 290. Chang Ling Lingen gate

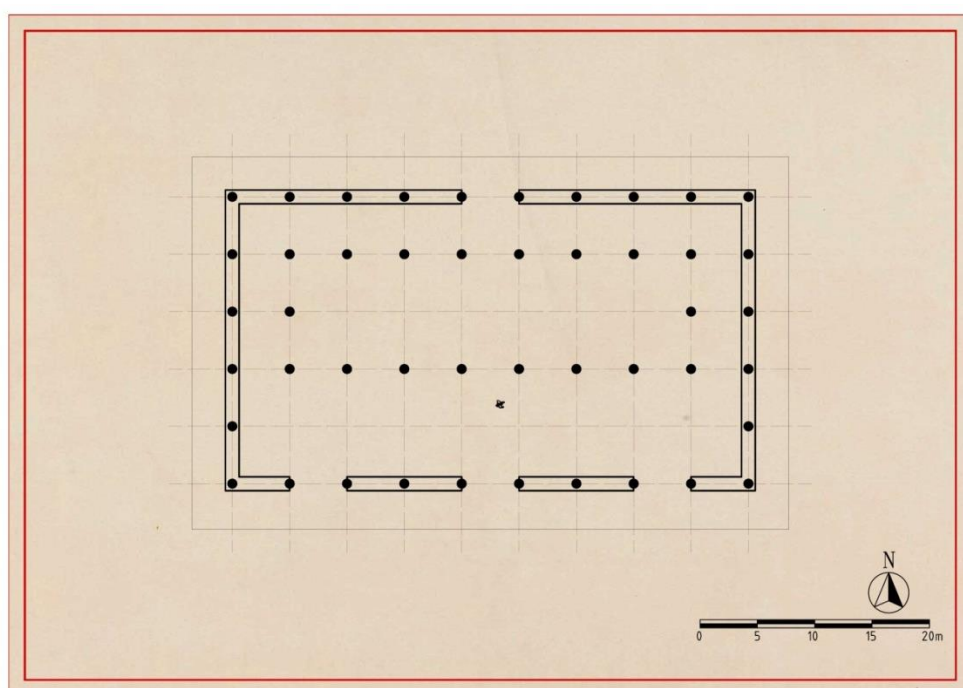


Figure 291. Fengguo temple major hall

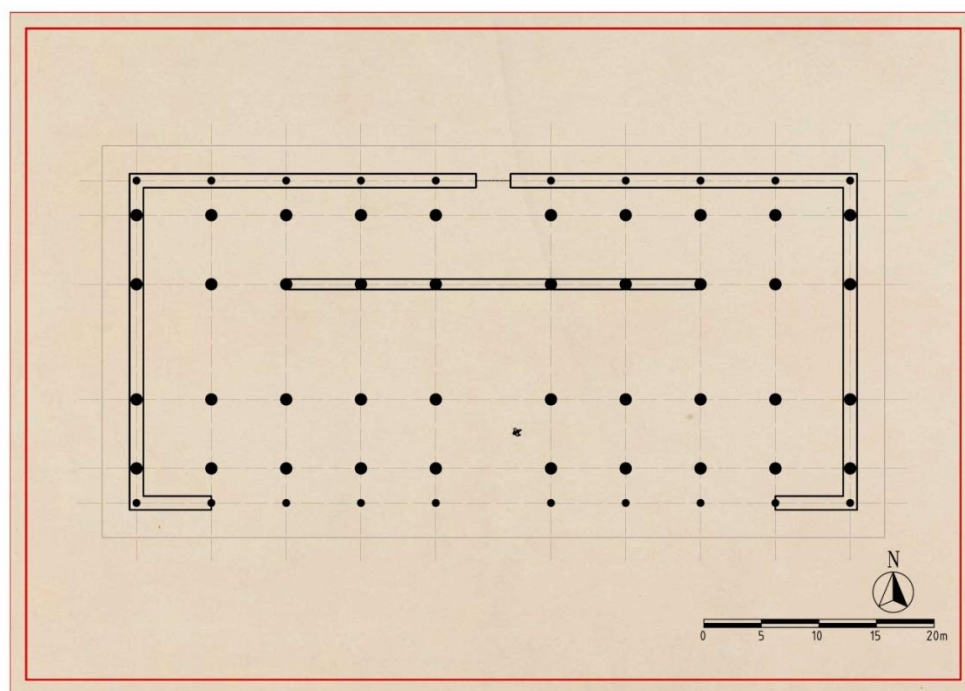


Figure 292. Lingen hall

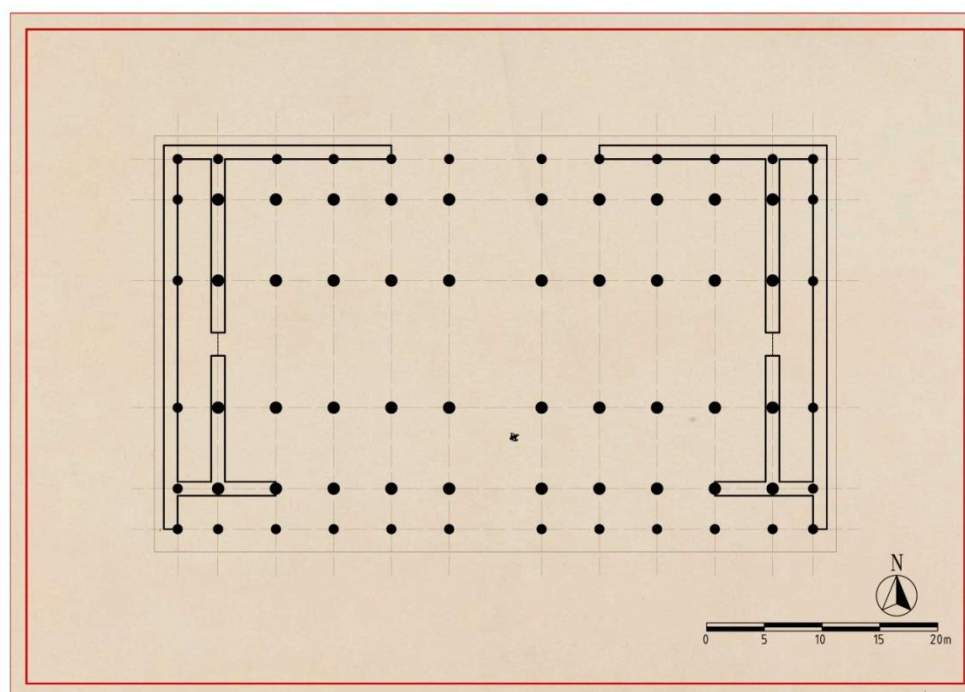


Figure 293. Taihe hall

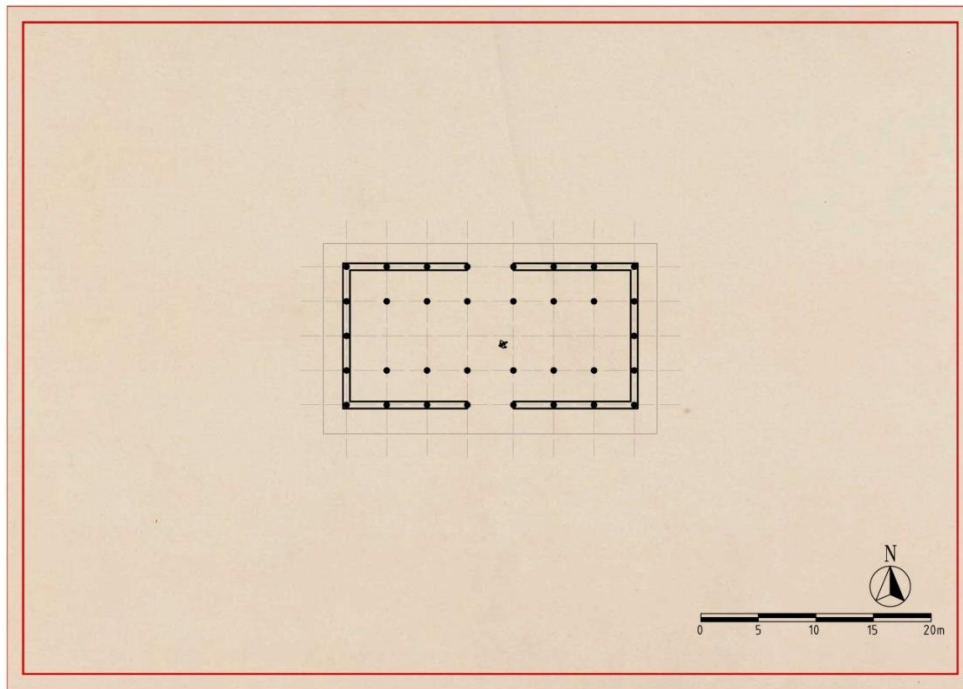


Figure 294. Computer generated 7-bay 4-rafter

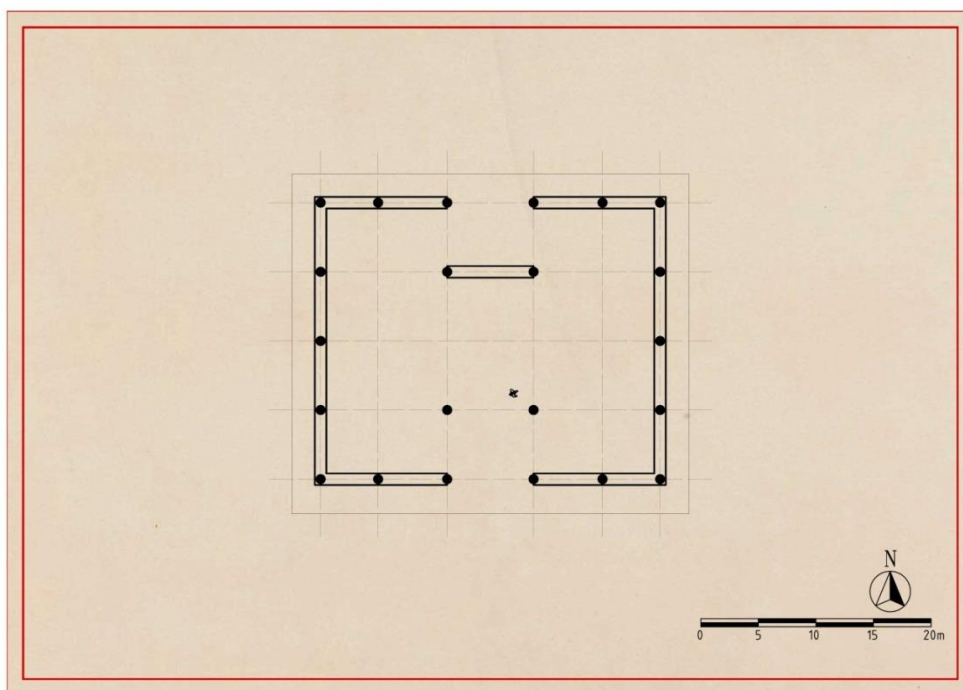


Figure 295. Computer generated 5-bay 4-rafter

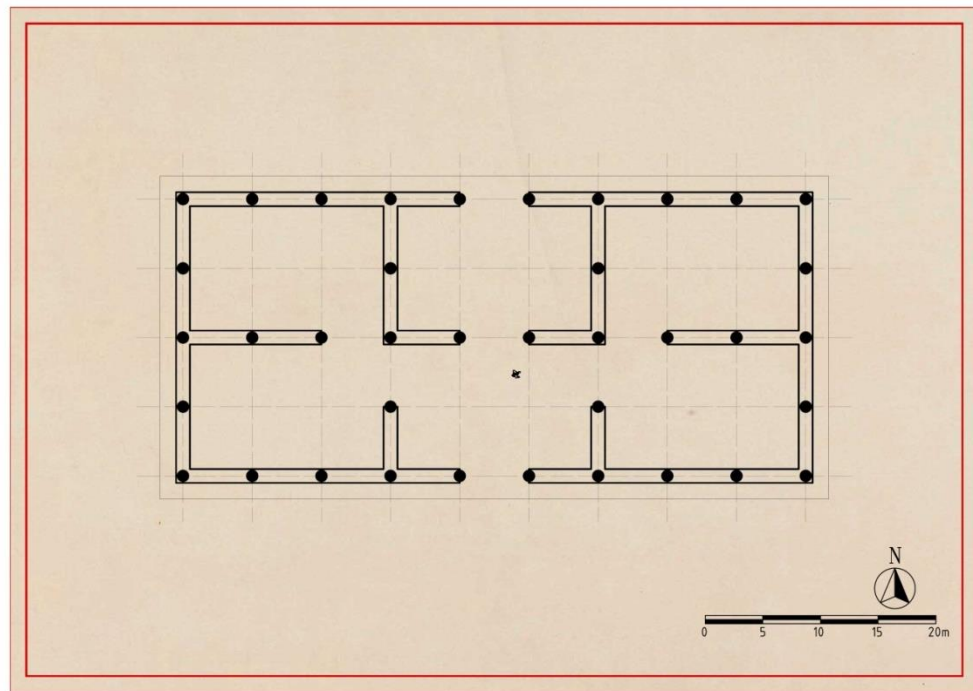


Figure 296. Computer generated 9-bay 4-rafter

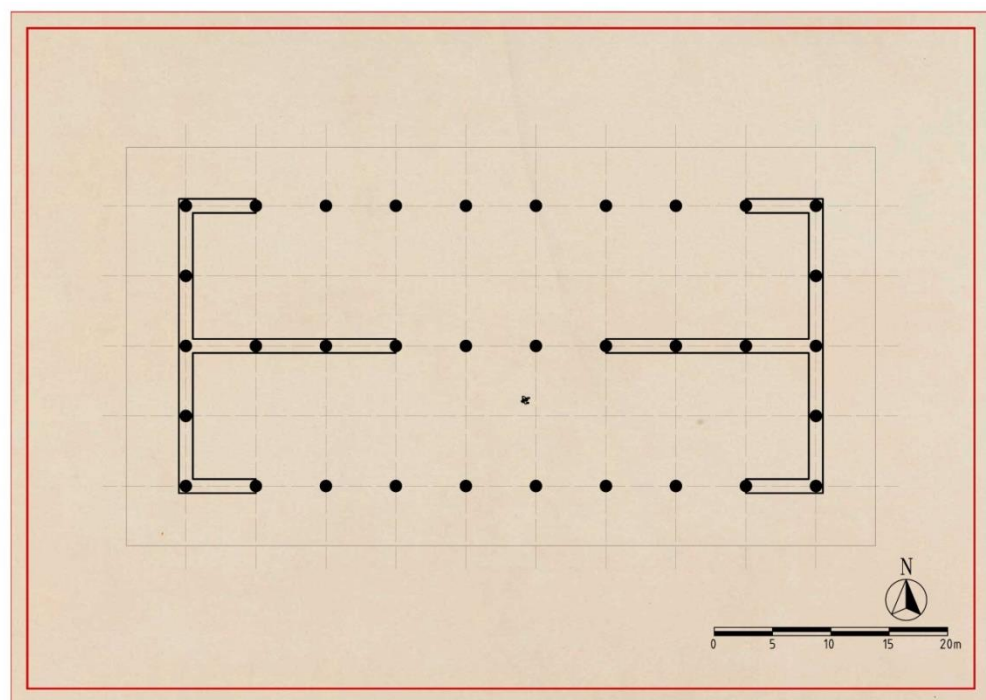


Figure 297. Computer generated 9-bay 4-rafter

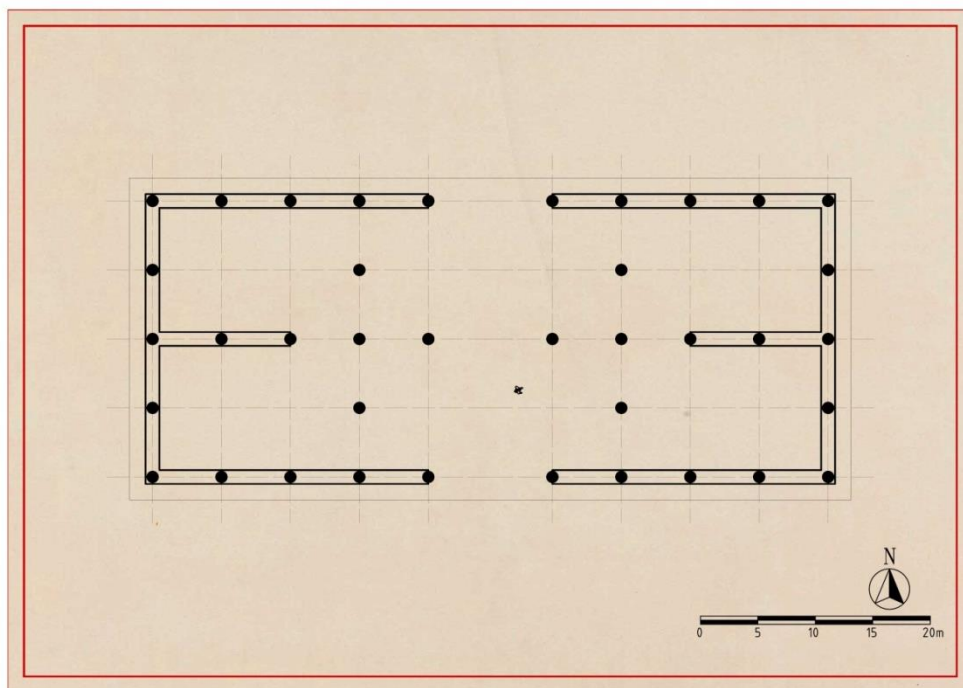


Figure 298. Computer generated 9-bay 4-rafter

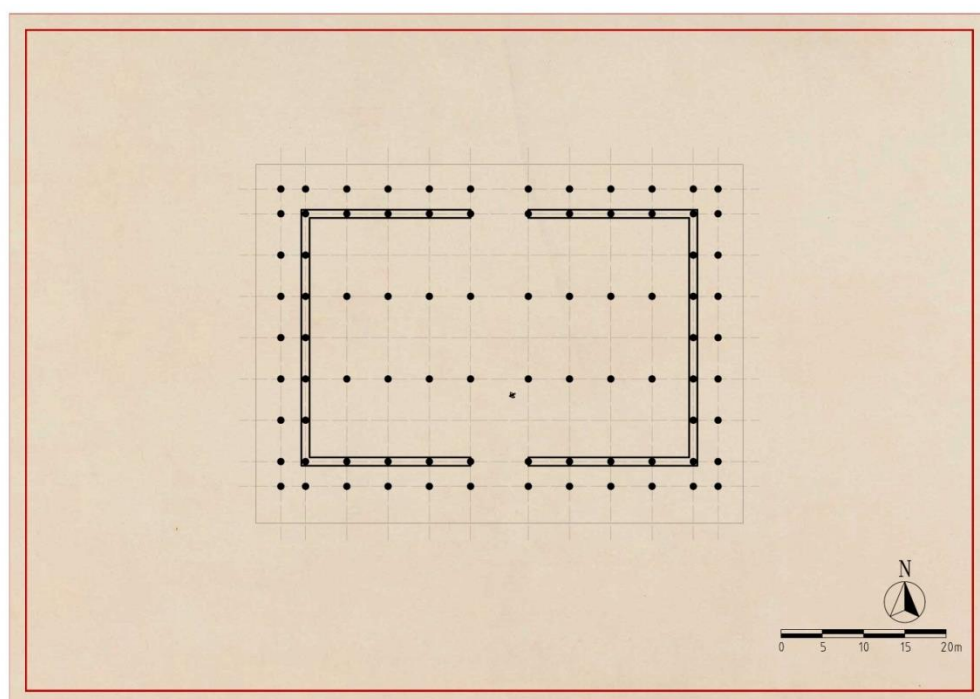


Figure 299. Computer generated 11-bay 8-rafter

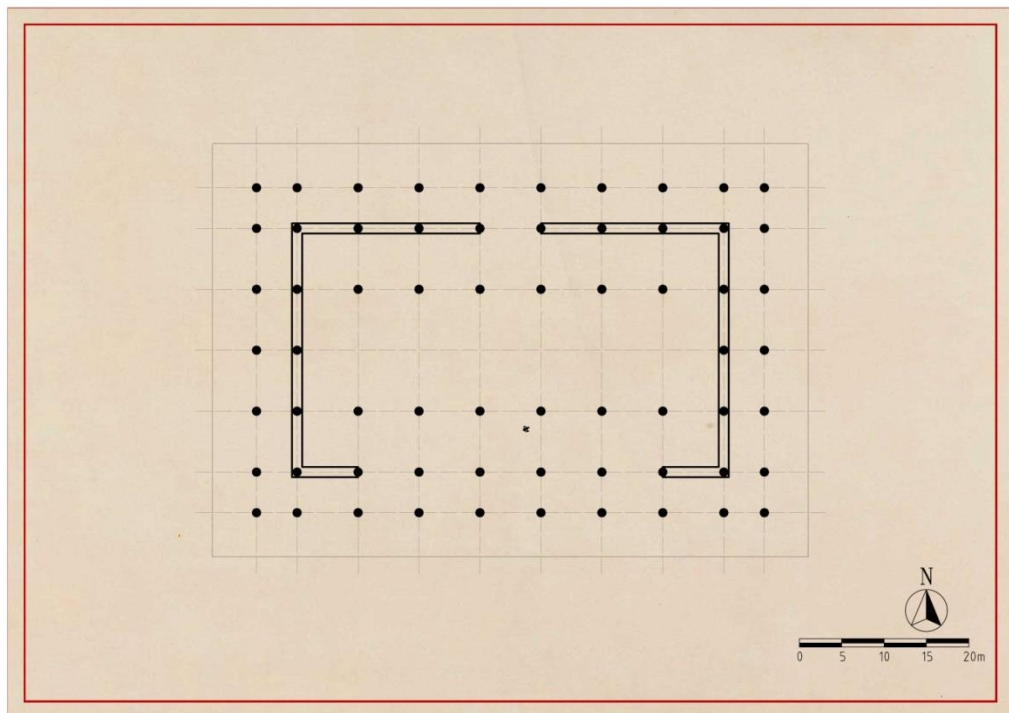


Figure 300. Computer generated 9-bay 6-rafter

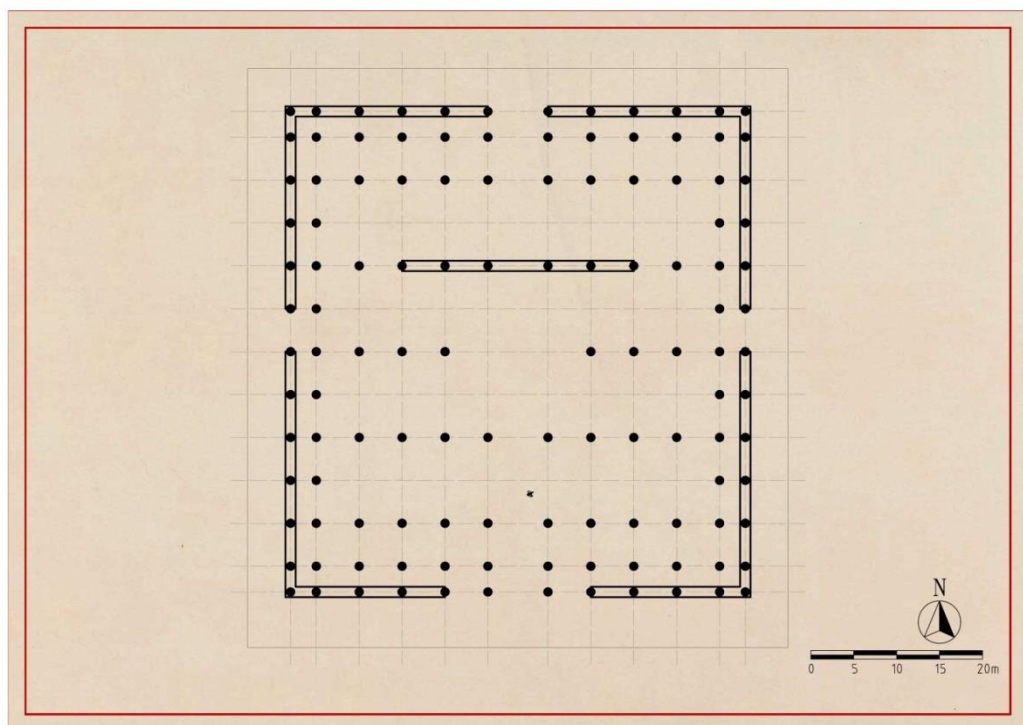


Figure 301. Computer generated 11-bay 12-rafter

Appendix 3 Published papers

eCAADe 2013 conference paper:

A Parametric recreation of traditional Chinese architecture--A case study on the floor plan (31th eCAADe Conference proceeding, 18th-20th Sep 2013, Netherlands)

A Parametric Recreation of Traditional Chinese Architecture

A case study on the floor plan

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Abstract. This paper presents the current state of progress investigating the possibility of modelling traditional Chinese architecture using parametrics based on the two rule books. This builds on the work of producing systematic analysis on both rule books and contributing knowledge from extant buildings. The case study target is the floor plan described in *Ying Zao Fa Shi*. Discussion and future works are suggested at the end.

Keywords. Parametric modelling, traditional Chinese architecture, *Ying Zao Fa Shi*, *Kung-ch'eng tso-fa tse-le*, floor plan.

INTRODUCTION

When studying traditional Chinese architecture, two references are essential—literary records and extant buildings. China, a country with over 5000 years of history boasts remarkable architecture from all dynasties and periods. Unfortunately, almost none of the buildings before Tang Dynasty (618-907) remain and many buildings from Song Dynasty (960-1279) to Ching Dynasty (1616-1912) have been badly damaged or destroyed.

However, two important texts survive: *Ying Zao Fa Shi* (Building Standards) from Song Dynasty and Ching Dynasty: *Kung-ch'eng tso-fa tse-le* (Structural Regulations) from Ching Dynasty, which are known as the “two text books of Chinese ancient architecture” (Liang, 1985). They are the only remaining classical Chinese literature which deals with architecture and are, in essence, rule books that govern most aspects of the design. As a starting point, the analysis on the two rule books is a key factor in understanding architecture of this period. This paper looks at generation of the floor plan using the *Ying Zao Fa Shi*. A series of rules and hypotheses are reviewed

before the generation of the floor plan models using Grasshopper and Rhino. The models are discussed and evaluated and additionally, the comparison with parallel research of the Shape Grammar approach to the floor plan is discussed.

THE TWO RULE BOOKS

Figure1 illustrates the chronological diagram indicating a brief history of China and the two dynasties (in the square boxes) in which the two rule books were compiled.

Ying Zao Fa Shi (Li, 1103) was the official building standard as a guidance of design and construction in Song Dynasty. During the period of the Song Dynasty, an increasing number of different levels and types of buildings were constructed which led to an urgent requirement of an official instruction. There were three original purposes of this book. First, to set the design guidelines to articulate the social status of feudalism. Second, to establish a unified architectural form and style to guarantee a consistent level of detail and artistic effects. Third, to define

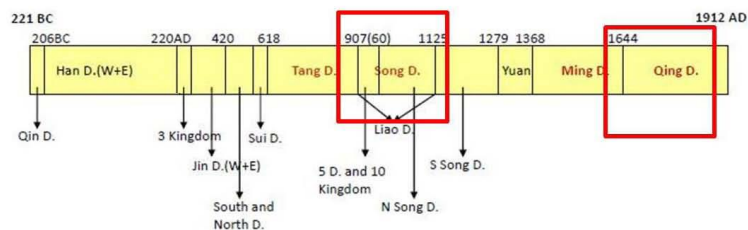


Figure 1
Chinese dynasties in chronological order.

the material choices and quantities as well as the work load to avoid corruption and embezzlement. The first edition was published in 1091 and with extended second edition compiled by Li Jie, the court architect of the Hui Zong Emperor in 1103.

This book consists of thirty-four volumes. Volumes one and two are the overall introduction to different types and components of the architecture. Volume three is about the foundations, masonry structures and carving of handrails. Volumes four and five introduce the structural carpentry system. Volumes six to eleven introduce the finished carpentry. Volume twelve includes three timber precast methods and bamboo weave method. Volume thirteen explains tile and cement processing. Volume fourteen focuses on the composition and colour matching of decorative painting. Volume fifteen describes the precast of bricks and ceramic materials. Volumes sixteen to twenty-five presents the work load required in the previous volumes. Volumes twenty-six to twenty-eight outlines the material consumption of the components mentioned above. Volumes twenty-nine to thirty-four are the selected diagrams.

The significance of Ying Zao Fa Shi is not "simply for its existing" (Li, 2001). The book is, in general, well organised, logical, systematic and rigorous which is quite rare in ancient literature. Although some aspects such as the floor plan are relatively lacking in systematic description, the whole book provides readers with a "rule-based and parametric" system (Li, 2001) for the ancient style buildings. Liang (1983)

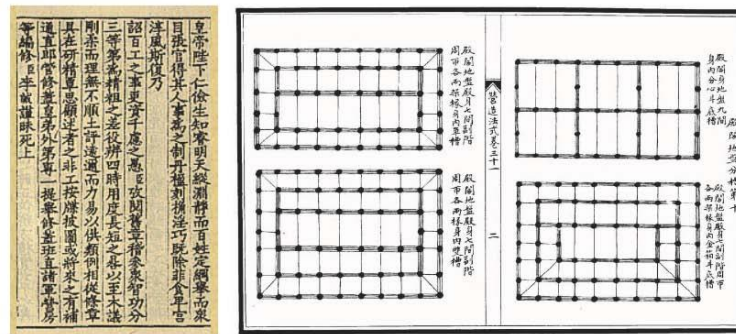
even points out that the Hui Zong Emperor was a naive politician, but was an excellent artist. Meanwhile Li Jie was also good at drawing and music. This might be one reason why occasionally Li Jie omitted some important descriptive rules but paid more attention to the architectural style and decoration. Together with Li's research (Li, 2001; 2003) and the on-going research in the case study on the ting tang section by the authors, it has been shown that Chinese traditional architecture has some parametric characteristics.

As shown in Figure 2, Ying Zao Fa Shi was written in an ancient form of the Chinese language which has no punctuation. The characters, vocabulary, grammar and text direction were all different from contemporary written Chinese which presents a big problem to modern researchers. In relative terms, Ching Dynasty: Kung-ch'eng tso-fa tse-le (1734) is linguistically more acceptable since it is compiled in 1734, more than six hundred years closer to us. Meanwhile, more extant buildings from Ching Dynasty can be studied as practical evidence. In this book, twenty-seven types of buildings with accurate size and dimensions are given as examples, making it useful for reconstruction of buildings of the period.

RULES FOR THE FLOOR PLAN AND PARAMETRIC APPROACH

In order to understand and recreate floor plans, a description of the ancient floor plan system is necessary. In Ying Zao Fa Shi, the following factors or pa-

Figure 2
Sample pages of Ying Zao Fa
Shi (left: text description [1];
right: floor plan diagram [2]).



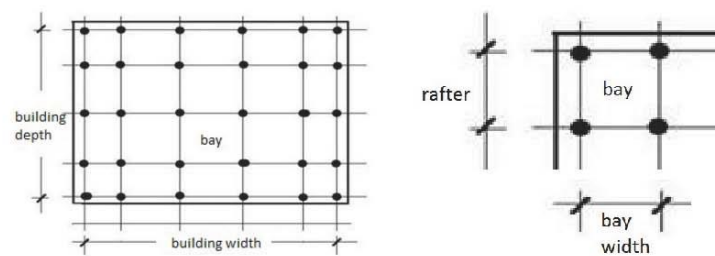
parameters can be used to describe a building:

- The building type (such as dian tang or ting tang, here tang means hall).
- The overall dimension (measured in modular unit):
- Building width (and bay width)
- Building depth (and rafters)
- The grade (which is used to calculate the absolute value of the modular unit)

In the most common and formal cases, the floor plan of a single house is rectangular and consists of two major factors: building width and building depth, which determines the dimension and scale of the house. The building width and building depth

form the area of a building. This area can be divided into small units (small rectangles) ie bays (usually, each bay has four columns at the four corners, although not in every case). Each bay is determined by the bay width and bay depth, as shown in Figure 3. The sum of the bay width or bay depth gives the building width or depth. But in reality, the bay depth is not described in the set of parameters above. Instead, the horizontally projected rafter is used to measure the depth. There are three reasons. First, Ying Zao Fa Shi mentions for ting tang type building, one bay depth equals to two rafters deep but it does not mention the relationship for the dian tang type building. Therefore in order to unify the parameters

Figure 3
Factors of the floor plan.



Size of fen (in cun)	0.60	0.55	0.50	0.48	0.44	0.40	0.35	0.30
Grades of dian tang	1	2	3	4	5			
Grades of ting tang			3	4	5	6		
Grades of other types						6	7	8

Table 1
Absolute values of fen for different grades.

	ting tang	dian tang
Building width (number of bays)	3,5,7,9 bays	3,5,7,9,11 bays
Building depth (number of rafters)	4,6,8,10 rafters	2,4,6,8,10,12 rafters
Bay width	200-450 fen	
rafter	≤ 150 fen	

Table 2
Definition of the four parameters.

in the later parametric modelling, the rafter is selected as the depth measurement for both building types. Second, to be consistent with the research of case study on the section, the rafter is a key parameter in defining the section. The rafter is closely related to the disposition of the columns and beams and the total number of columns. Third, from the workers' experiences, they tend to use rafters rather than bay depth. Apart from the rectangular forms, there are also several non-rectangular floor plans, known as non-formal architecture, which includes the use of the triangle, circle, sector, octagon, polygon, and the superposition of polygons and Wan shape. They are widely used in pavilions and gardens which typically appear in Southern China. But these irregular shape floor plans are not discussed in this paper.

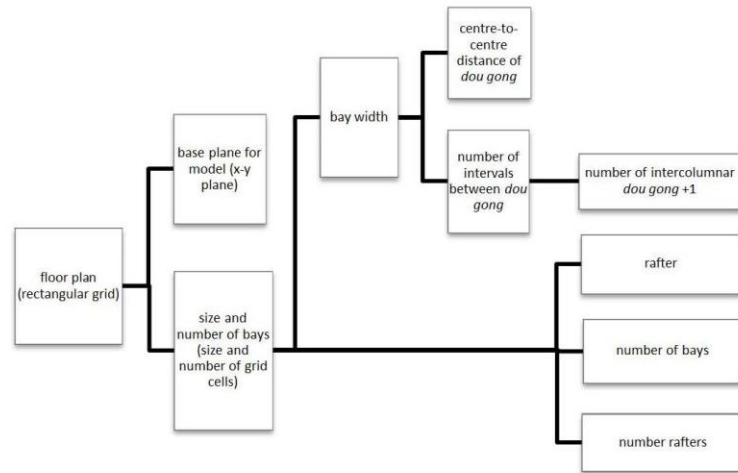
At this point, it is worth describing the measurement units used. Depending on the eight grades of the buildings, a fen can have eight different absolute values (Liang, 1983), measured in cun (a Chinese length unit), as shown in Table 1. Given that 1 cun = 32mm approximately in Song Dynasty, the final absolute values of width and depth can be obtained. For example, if the building is ting tang type and in Grade Three, 1 fen = 0.5 cun × 32mm/cun = 16mm.

In order to build up the parametric logic, there are four more details which need to be clarified: the value of bay width and rafter, and number of both (which constitutes the building width and building depth). Unfortunately, at this stage, Ying Zao Fa Shi does not provide a systematic definition. Instead, it gives information partially by defining and partially by enumerating. Despite this, the parametric model

could still be built up by first making hypothesis based on the information in hand and then evaluating with the diagrams in the rule book and extant building measurement data. The assumptions here are based on the investigation of historian Chen (1993). As shown in Table 2, the four parameters are summarised. In particular, the bay width is not given directly. The calculation is as follows: a bay has two sets of dou gong (the bracket joint) that sit on each side of the columns (the black dots in Figure 3) and either one or two sets between the columns (inter-columnar dou gong). The centre-to-centre distance of dou gong is 125 fen ± 25 fen. Thus the bay width with one intercolumnar dou gong is 250 fen ± 50 fen, and with two intercolumnar dou gong is 375 fen ± 75 fen. Therefore the total range of bay width is 200-450 fen. In addition, the centre bay is often wider and in most extant examples the two outer bays are often slightly narrower than the others [3]. In the table, the modular unit fen is used rather than the absolute values.

After all the parameters are clarified, the parametric model now can be built. Figure 4 shows the logic diagram for the parametric modelling. In this logic diagram, ting tang and dian tang types are integrated together since Liu (1984) points out that "although Ying Zao Fa Shi distinct the two types strictly, buildings are slickly dealt with in practice". The rectangular floor plan grid is set first by defining the x-y plane as the base plane. The next step is to define the size and number of bays. In order to achieve this, the four parameters described above are outlined here. As the primary parameters, the

Figure 4
Parametric logic diagram.



rafter, number of bays and number of rafters can be directly controlled by the corresponding number range listed in Table 2. The bay width is a multiplication of two factors: centre-to-centre distance of dou gong and number of intervals between dou gong. Additionally, the number of intervals between dou gong is equal to the number of intercolumnar dou gong plus one. Since the number of intercolumnar dou gong is known directly, this is the fourth parameter. Thus, overall, there are only four simple parameters that can be controlled depending on the building type and grade. In addition, there is one judgment in this logic diagram: the building width should always be larger than the building depth. And if so, the conclusion will appear true. Under this one set of logic diagrams the floor plan of both ting tang and dian tang types, all eight grades of building with different bays and rafters are involved. Figure 5 shows two examples of the model.

Comparing the examples with the diagrams

in Ying Zao Fa Shi (Figure 2 right), they are highly consistent in form. And there is one extant building example—Fuoguang Temple Wenshu Dian (Figure 6), which built at 1137, located at Shanxi Province. It is a Grade Two dian tang type building with seven bays. From the parametric model, the minimum building width is given as $7 \times 200 \times 0.55 \times 32 = 24640 \text{ mm} = 24.64 \text{ m}$ while the maximum is $7 \times 450 \times 0.55 \times 32 = 55440 \text{ mm} = 55.44 \text{ m}$. Similarly, the building depth spans from 15.84m to 21.12m. Wang (2011) provides its measurement data of 31.56m in width and 17.60m in depth. As Liu (1984) argues that “there is not such an extant building completed follows Ying Zao Fa Shi found so far”, if the measurement data is within the range of the parametric model, then the two are consistent.

DISCUSSION

Parametric design differs from the conventional design mode of adding and removing marks in that

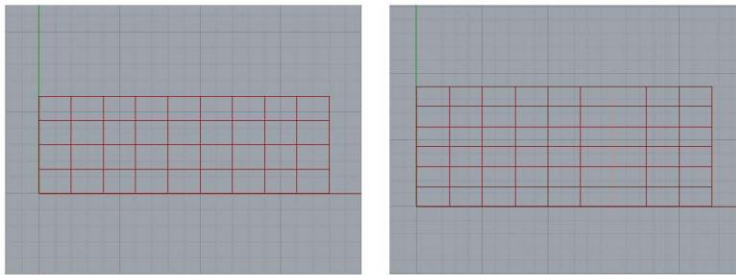


Figure 5
Examples (left: 9 bays 4 rafters
floor plan; right: 9 bays 6 raft-
ers floor plan).

the relationships between the parameters are the essence of parametrics. In this case study, the relationships are not based on one specific example, but a systematic description and summary of all the buildings in a typical period—which are the rules. The logic diagram of the formal rectangular floor plan is then built up based on the rules. Following this, different outcomes can be generated to indicate the advantages of parametric method which can result in different final products without a new set of logic diagrams or the removal/addition individual components. In particular, all the floor plan formats are included in this set of logic diagram, including both the building types (dian tang and ting tang), any dimensions and all the grades.

There is parallel research in the Shape Grammar approach to the floor plan (Li, 2001). In the research, Li derives the process with initial symbols

and a set of rules, and then the design rules act on the initial symbols repeatedly, resulting in a final design. Following each typical set of rules will result in one corresponding final design. Thus Shape Grammar generates a language of design. How and in what sequence do the rules applied makes up the so called grammar? Compared with Li's research (Li, 2001), the advantage of the parametric method is the ease with which the process can be extended into three dimensional modelling. For instance, the intersectant points could be the column locations when combining with the case study on the section. Then, the two dimensional representation of architecture through the plan and section will form the three dimensional parametric model. And indeed, according to Wang (2011), more special proportions (relationships) exist in the elevations, as well as many other building factors. On the other hand,



Figure 6
Fuoguang Temple Wenshu
Dian [4] [5].

if all the attempts are limited in two dimensional planes, it may omit rules and relationships that exist between the section and the floor plan.

CONCLUSION

Accordingly, three major similarities between Shape Grammar and parametrics can be drawn. Both of them are derived systematically and logically; both of them are generative and productive; both of them can be symbolically and graphically illustrated. In contrast, three key differences can be identified as well. The parameters in parametric method can be any variables, abstract or concrete, without the limitation of just geometrical entities. The rules used in parametrics can be any logic relationships, not only repetitions and the final outcome could involve many different variations.

When combined with parallel work in the parametric generation of the ting tang section, it is found that the characters summarized from deriving the floor plans are consistent with those from generating sections. Taking Li's work (Li, 2001) of shape grammar approach to the floor plan and ting tang section into consideration, it can be concluded that Chinese traditional architecture has parametric characteristics. Since the whole structure of traditional buildings constructed using the rule books is complex and closely interrelated, a parametric method has the advantage of illustrating and generating the principles from the rule books to complex digital reconstructions. The application is not limited to the restoration of ancient building, but could also be used as inspiration in the generation of new designs. Apart from individual buildings, based on the floor plan logic diagram, a similar parametric method can be used in recreation of many city plans, since several Chinese ancient cities also show parametric characteristics.

REFERENCES

- Chen, M, 1993, *A study of structural carpentry in the Ying Zao Fa Shi*, Wenwu, Beijing.
- Ching Dynasty, 1734, *Kung-ch'eng tso-fa tse-le* (Structural Regulations).
- Gips, J, 1975, *Shape Grammars and their Uses*, Birkhauser, Basel.
- Li, A, 2001, *A shape grammar for teaching the architectural style of the Ying Zao Fa Shi*, MIT, Cambridge, MA.
- Li, A, 'The Yingzao fashi in the information age', *The Beaux-Arts, Paul Philippe Cret, and Twentieth Century Architecture in China*, The University of Pennsylvania, 3-5 October 2003.
- Li, J, 1103, *Ying Zao Fa Shi* (Building Standards).
- Liang, S, 1983, *Ying Zao Fa Shi Zhu Shi* (The annotated Ying Zao Fa Shi), China Architectural Industry Press, Beijing.
- Liang, S, 1985, *A pictorial history of Chinese architecture: a study of the development of its structural system and the evolution of its types*, MIT Cambridge, MA, pp.1-16.
- Liang, S, 2006, *Analysis on Ching Dynasty: Kung-ch'eng tso-fa tse-le* (Structural Regulations), Tsinghua University Press, Beijing.
- Liu, D, 1984, *Chinese ancient architectural history*, China Architectural Industry Press, Beijing.
- Stiny, G, 1980, *Introduction to Shape and Shape Grammars*, Environment and Planning B, 7.
- Wang, G, Liu, C and Duany, Z, 2011, *The research on proportion of Chinese ancient timber frame architecture*, China Architectural Industry Press, Beijing.
- [1] http://andrew.li/yzfs/yzfs_new/b2.htm (accessed 15 May 2013)
- [2] <http://dl.zhishi.sina.com.cn/upload/61/88/61/1146618861.9708083.jpg> (accessed 15 May 2013)
- [3] http://andrew.li/yzfs/yzfs_new/b11.htm (accessed 15 May 2013)
- [4] http://www.lzy.cn/travel_photo/e30/155133.html (accessed 15 May 2013)
- [5] <http://www.panoramio.com/photo/32278856> (accessed 15 May 2013)

eCAADe 2014 conference paper:

Digital fabrication as a tool for investigating traditional Chinese architecture-- A case study of the dou gong (32th eCAADe Conference proceeding, 10th-12th Sep 2014, UK)

Digital fabrication as a tool for investigating traditional Chinese architecture

A case study of the dou gong

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This paper presents part of a broader research project in which a set of complementary computational techniques have been applied to investigate and interpret traditional Chinese architecture. The techniques involve digital modelling, algorithmic representation and digital fabrication. The ancient rule books that describe the traditional Chinese design styles and construction technologies are the basis for the parametric rules and algorithms and the application to the modelling and fabrication process. The focus of this paper is the study of a typical Chinese joint structure, the dou gong. The precedent case study and the components of the dou gong are reviewed and analysed. Then the digital representation and fabrication processes that have been employed are demonstrated. Practical problems were found in this process and modifications were consequently made. At the end of the paper, we discuss the achievements and benefits that arise from this investigation, and potential applications in practice. Conclusions from work presented in this paper and for the broader research are drawn respectively. Significant prospective work is suggested.

Keywords: dou gong, Ying Zao Fa Shi, digital fabrication, traditional Chinese architecture

INTRODUCTION

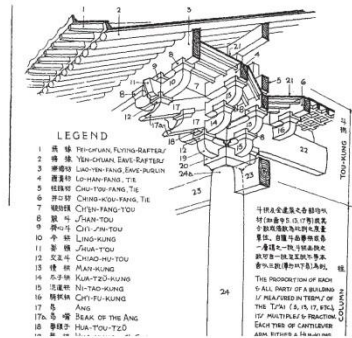
China is one of the Four Great Ancient Civilizations which has a span of over 5000 years and its traditional Chinese architecture plays a significant role in the world's architectural heritage. Unfortunately, almost all the buildings constructed before the Tang Dynasty (618-907) have disappeared. However there are some buildings from the period from the Song Dynasty (960-1279) to the Ching Dynasty (1616-1912) remaining, but in differing states of repair.

With the rapid development of digital techniques in architecture over the last 25 years, it is possible to re-discover the value of the lost or damaged architecture by transforming two dimensional physical information recorded in the historical literature into three dimensional digital representations (Webb and Brown, 2011). Using parametric and shape grammar techniques (Li, 2001; Wu, 2005) it has been shown possible to describe the relationships in a digital design environment that describe the traditional de-

signs in an algorithmic way (Li et al. 2013). Consequently, further analysis can be made together with a better level of understanding and interpretation. In turn, this can significantly aid understanding, in restoring and recreating examples of traditional Chinese architecture, or in designing contemporary examples that respect traditional geometries and val-

historical period. The joint plays a multi-functional role that covers structure and construction requirements as well as being an essential component of the aesthetic qualities of the whole construction. As Liang (1985) points out, "the *dou gong* plays the leading role, a role so important that no study of Chinese architecture is feasible without a thorough understanding of this element, the governing feature of the Chinese 'order'."

Figure 1
dou gong (Liang,
1985)



This paper is part of a broader research investigation into the digital interpretation and recreation of traditional Chinese architecture. We do so by turning ancient rule book information into algorithms and applying these in a contemporary parametric modelling environment. This paper concentrates on the understanding, representation and digital fabrication of a typical Chinese joint structure, the *dou gong*. This is a particularly complex aspect in the design of traditional Chinese architecture, as there are many elements to the joint that have a sophisticated relationship with each other, as shown in Figure 1 (Liang, 1985), and there are many variations according to the scale, location, function, decoration and

CASE STUDY OVERVIEW AND PRECEDENT

There are the only two surviving ancient rule-books: *Ying Zao Fa Shi* (Building Standards) from Song Dynasty (960-1279) and *Ching Dynasty: Kung-ch'eng tso-fa tse-le* (Structural Regulations) from Ching Dynasty (1616-1912), which are referred to as the "two text books of Chinese ancient architecture" by Liang (1985). According to Li (2001), *Ying Zao Fa Shi* is rule-based and indicates parametric characteristics. The joint, called the *dou gong*, is described in one of the carpentry volumes in *Ying Zao Fa Shi* (Li et al. 2013), which is the bracket set on top of the columns and under the beams and the roof.

To understand the *dou gong* parametrically, two approaches can be taken. First, the *dou gong* is treated as a whole rather than focusing on each individual element and the modelling process concentrates on building up the whole structure and setting up the position of all the elements. Then detailed elements are dealt with later. This is the top-down method. The second involves the construction of each element first and then connecting them together. This is the bottom-up method and the concentration of this paper, which will be discussed in detail in the following sections.

Following the first approach, a graphical representation is made as shown in Figure 2 using Grasshopper. Since the main structure of *dou gong* is doubly symmetric, in order to construct the model efficiently, one fourth of a complete *dou gong* is built up. By mirroring twice, a complete *dou gong* could be carried out. This is a conceptual model which is based on a commonly used concept of the tree

Figure 2
The top-down
approach of dou
gong

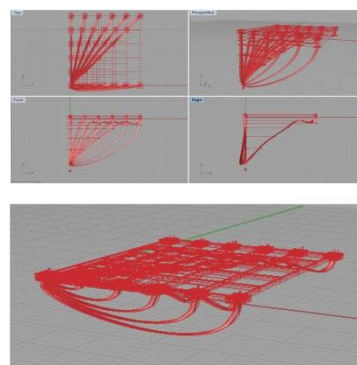
Figure 3
The top-down
approach of dou
gong using the
Gaussian function

branches. Several layers of the tree branches grow and expand outwards, which generates the extended tree canopy. In this process, the iterative layers and extension of each layer are the key factors for simulating the bracket set. To achieve this, first of all, a series of points are set up along the Z axis. This provides the initial partition of the layers, which are the basis for *gong* (the long arms). The number of the layers is controlled by an input slider which can be changed based on the need of layers. The Graph Mapper is an effective method in the controlling. Then the parabola function is selected to generate all the points locating the tree branches (representation of *gong*). The strongpoint of parabola function is to be able to easily define all the layers together. But from the later process, it is found that this might lead to the loss of control of the branches shape within each layer. To improve this shortage, the Gaussian function is introduced to replace the parabola function in this process. As shown in Figure 3, the shape of the branches is closer to the *gong* described in the rule book. Following this, a rectangular grid of points is set up within each layer. The area of layers reduced gradually from the top to the bottom along the Z axis. Here Path Mapper is used to arrange the location of points within each layer. Then, building up all the branches by lofting the curves based on the grid of points. In this process, it is noticed that although the position of the *gong* (tree branches) is defined, the position of the *dou* (the small rectangular blocks) is omitted without a clear definition and consideration. But actually from Figure 2 (top view), it is shown that the small square of grid within each layer could be used as the position of *dou*.

From this experiment, we note three points of merit. First, the layers and extension within each layer are achieved. This is a basis to recreate different scales of the joint without the need for another set of logic definitions. In addition, this attempt can fulfil some of the main functions stated in the rule book, such as the potential to enlarge the roof area both outwards and inwards. Thirdly, the configuration can be adjusted by controlling all the input pa-

rameters. This enables the possibility of the achievement of the aesthetic function of the joint, that is, to treat the joint as a pure classic decoration. And indeed, since the Ming Dynasty, the structural function has become less important due to the development of other constructional technologies while the aesthetic value became more emphasized.

On the other hand, several problems were observed. The accurate shape of the joint is not represented well in the experiment; as well as its volume, an extra set of logic relationship which defines the precise shape and volume of the joint is needed. This is necessary to guarantee the achievement of other important functions of the joint (which will be introduced in the following sections). In addition, the accuracy of each element of the joint is also omitted. Apart from these matters, there is a key component which acts as a lever in the function, omitted from this model. The above problems lead to the adoption of the second approach described in the following sections.



DOU GONG (THE JOINT)

In order to investigate the detailed elements of the *dou gong*, an understanding of its development and structure is helpful. From the first appearance of *dou gong* in period of the Warring States (approx. 475BC-221BC), it developed and changed up to the time when *Ying Zao Fa Shi* was written. This guide outlined a relatively systematic description and established a standard. Later in the Ming Dynasty (1368-1644) and Ching Dynasty, it was further developed into a more complex artefact. Apart from the format, the name of the *dou gong* components also changed during the development. Since the two rule books are the only available ancient references, the name labelling system currently used follows the earlier rule book, *Ying Zao Fa Shi*. In this way the names used in this paper will also be consistent with the broader research work of the authors.

To gain an overall impression of the joint, Liang's research work (2001) is significant. According to Liang (2001): The base of the joint is a large square block (*dou*) on the top of the column. There are set into that block crossed arms (*gong*) spreading in four directions. These in turn bear smaller blocks (*dou*) that carry still longer arms spreading in the four directions to support upper members in balance. The jutting arms (*hua gong*) rise in tiers (*jumps*) and extend outward in steps from the large-block fulcrum to support the weight of the overhanging eaves. This external pressure is countered by internal downthrusts at the other ends of the bracket arms. Intersecting the *hua gong* in the bracket set are transverse *gong* that parallel the wall plane. Long cantilever arms called *ang* descend from the inner superstructure, balance on the fulcrum, and extend through the bracket sets to support the outermost purlins. This outer burden is countered by the downthrust of upper interior purlins or beams on the "tails" of the *ang*. The extruding "beaks" of the *ang* easily identify them in the bracket sets.

There are five main functions in terms of the aspects of structural, mechanical and aesthetic functions. Firstly, it is located between the column and

the roof as shown in Figure 1, transferring the roof load evenly through the column to the foundation. Second and most distinctive one is to provide an earthquake-resistant function. Since all the horizontal and vertical components insert into each other following a prescribed order and rule without any mechanical fixings or glue, its elastic performance can absorb both horizontal and vertical earthquake waves. Previous records show that many traditional buildings with *dou gong* such as the Forbidden City perform very well during earthquake disasters (Liang, 1985). Third and most practical the *dou gong* can support the outwards enlarged roof area to better protect the walls and windows from heavy rains but at the same time prevent the blockage of the daylighting from the pendulous roof edge. It is especially important because in ancient periods traditional windows are made of paper and the main structure of the buildings are made of wood, both require water proof mechanism. An example discovered by Liang (1985) is Fuoguang Temple major hall (built at 857), the extent of eaves project about four meters out from their supporting columns. "Their importance in sheltering the wooden structure from weather damage for over 1100 years is, they throw away from the building the rainwater that courses down the tile troughs of the concave roof" (Liang, 1985). Fourthly, the *dou gong* also extends inwards to shorten the span of the beam and *fang* so the stresses on the beam and *fang* are reduced. Apart from the structural and mechanical functions, the *dou gong* also has aesthetic functions, which are not dispensable although it is normally hidden under a large roof. Factors such as the size and complexity, as well as the style and colour of the *dou gong* indicates the level of importance of the building itself, and that further implies the social status and richness of the building owner. For example, the royal style *dou gong* was strictly forbidden in civic buildings in ancient dynasties.

Depending on the location within the building, there are mainly three types of *dou gong* as shown in Figure 4. *Zhuan Jiao Pu Zuo* (*dou gong* at the corner,

Figure 4
Three main types of
dou gong (Liang,
2001)

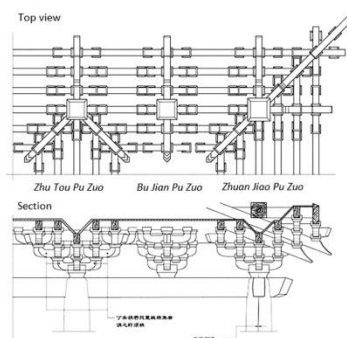


Figure 5
Components of the
dou gong (Edited
by the authors
based on Liang,
2001)

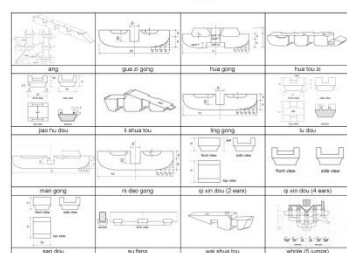
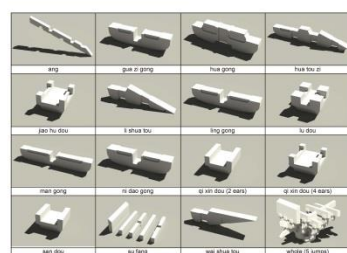


Figure 6
The component
parts



connect with column, support the corner beam and roof corner, and this is the major structure component), *Bu Jian Pu Zuo* (*dou gong* not at the corner, not connect with column, this is the assistant supportive component) and *Zhu Tou Pu Zuo* (*dou gong* not at the corner, connect with column, this is the main support of the eaves load). The measurement of the size of *dou gong* is *Pu Zuo* and normally there are four to seven *Pu Zuo dou gong*. Within each *dou gong*, fifteen key elements can be summarized in three categories: *dou*, *gong* and *ang*. *Dou* is the blocks under and to give support to *gong*, or on top of and at the two ends of *gong* in order to provide vertically extension to an upper layer of the *gong*. *Gong* is the long bracket arm supported by *dou* and to extend horizontally the area of the whole structure. *Ang* performs as a balance lever inside the joint. Different types and *Pu Zuo* of *dou gong* has different prescribed order to insert serials of *dou* and *gong* and other minor elements together. Details of fifteen key elements and the overall assembly orders are illustrated in Figure 5. The example used here is a five *Pu Zuo dou gong* in Song Dynasty based on *Ying Zao Fa Shi*, since five *Pu Zuo dou gong* has the suitable complexity which clearly shows all the major components, but does not have too many repetitions of each component. Therefore it is used as a typical case study example for the research at the starting point. Once it is clearly understood, other types and sizes of the joint could be similarly treated.

DIGITAL REPRESENTATION AND FABRICATION

Based on the description of the *dou gong* elements above and detailed rules, a set of fifteen digital models have been generated as shown in Figure 6. At this point, since the digital model is parametric, the real units are omitted. Instead, all the measurements are made based on the proportions, or in other words, the relationships between each segment. With the proportions, eight grades of the buildings have different units and absolute values to use in construction period (Li et al. 2013).

Due to the complexity of the *dou gong*, the main issue identified during the modelling process is how to guarantee the accuracy of all the components, including the connections between different surfaces, the precise curvature of the shapes, the correct dimensions of the components which may partly omitted in the rule book. To solve these issues, several experiments were undertaken. To merge the surface connections together and prepare for the later printing process, inspections were made both automatically and manually. The gaps on the outer surfaces were normally easy to find while the overlapping of surfaces inside a volume was difficult to detect. If this occurred, the target component must be "opened" and problem areas must be fixed manually. But in general, since the software used (i.e. Rhino/Grasshopper) is parametrically based, the manual fix work was only done when necessary, in a rate of about less than ten problem areas out of thousands of surfaces. Therefore, the overall process is still much advanced than the traditional way of checking the carpentry work surface by surface solely by the carpenter. Regarding the precise curvature of the shapes, there are mainly two different types. The curvature of the *dou* at the lower part of the block is a real curve where the curvature is based on other dimensions of the block. But the "curvature" of the *gong* at the both ends is made using several straight lines rather than a real curve. Apart from these, some omitted details or unclear descriptions also occurred in the rule book which brings difficulties in the modelling process. An essential way of solving this is to confirm the information of all the related nearby components and then derive the absent information then get a reasonable assumption. After this, put the assumption component back to the whole model and check whether it is consistent with the nearby components or not. Several components such as the hollow parts of *ang*, the slope of *li shua tou* and *wai shua tou*, the middle supportive part of *hua tou zi* were carried out by this method.

From the above evaluation, a revised version of the models was produced. Conventional fabrication

of the joint would be in wood. In digital fabrication, many options were open to us such as powder, wax, plastic, metal and, less common, paper. In this research, a relatively recent 3D digital fabrication technique using built up sheets of paper (3D Printer Matrix 300+) was selected for the following reasons. Paper, compared with plastic, is a sustainable material which does not pollute the environment and when laminated together in multiple layers, it becomes very strong and rigid compared to powder and wax. At the same time, compared with metal, the micro space between sheets can be compressed when needed, which maintains the elastic character of the traditional wood material and also the function of the joint. And this feature gives advantage when assembling the components: even without pre-defining the tolerance, different components can insert into each other tightly but without damaging the contact surfaces. This advantage is also discussed later in the tolerance discussion. For comparison, a powder model version was used as a comparison but showed that it is less appropriate than the one made using paper because the powder components were relatively weak and fragile and therefore not suitable for assembly and re-assembly.

In order to make full use of the 3D printer and produce the component parts effectively, all the 43 pieces of the fifteen elements (due to the repetition of some elements) digital models are carefully organized according to the geometrical shapes so that they can be composed within one stack of paper which is the raw material that the MC or 3D printer uses. Consequently the joint could be completed in one printing, as shown in Figure 7.

PRACTICAL PROBLEMS, MODIFICATIONS AND ASSEMBLY

During the process of extracting the components from the paper block and peeling off the spare material, practical problems arose with the *jiao hu dou*, *qi xin dou* (two ears), *qi xin dou* (four ears) and *san dou* constructions. In the paper stack, in order to save space to a maximum level, these small scale *dou* are

arranged in a position such that they partially interlock. However in practice it proved very difficult to extract each individual component without damaging the faces of an adjacent component.

Figure 7
The components are composed in the digital model to allow fabrication from a single block

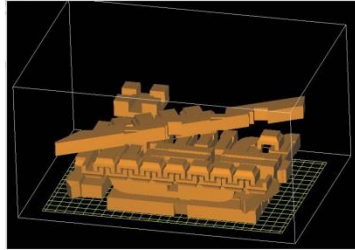


Figure 8
Modifications of the models

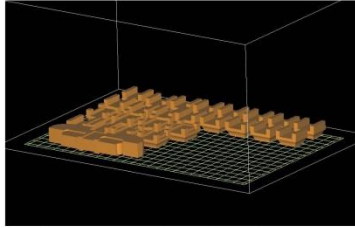


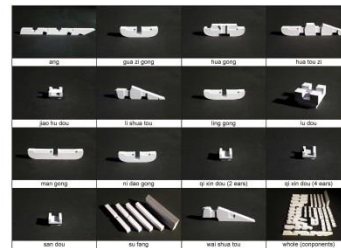
Figure 9
The digitally fabricated paper components

Modifications were made to these five elements in fabrication process. They are arranged as a single layer without overlap. With this arrangement, the small delicate parts could be extracted without damage, as shown in Figure 8. This is also the quickest way to reproduce these pieces considering the paper 3D printer makes the fabrication layer by layer (sheet by sheet). And indeed, this single layer models could also be properly arranged into the previous composed models of one paper stack and be printed once. After this, all the elements are assembled to complete the *dou gong*. Figure 9 shows all the physical models of components and Figure 10 shows the assembly process of the physical models.

DISCUSSION AND CONCLUSION.

After assembly, because the construction is extremely closely fitting, an analysis of the degree of error in the fabrication process was made by accurately measuring the dimensions in-plane and across-plane using a digital caliper, to ensure that it was within an acceptable level. The tolerance is shown in the Table 1. The majority of the tolerances measured proved to be good and the average tolerance was 0.94%.

Compared with conventional handmade techniques, obvious advantages were demonstrated. When producing the joint by digital fabrication, the modelling process is efficient such as the components can be reused in other types of the joints if they share some parts the same, without doing the "analysis, assumption, checking" process again. And when the overall scale needs to be changed, the digital models can easily achieve this. What is more important, industrialization is the trend to gradually replace handmade method to increase the productivity, standardize the process and optimize the outcome products. And indeed, today there are very few knowledgeable and experienced carpenters who can be found in this area which has led to a gradually disappearance of this kind of traditional construction. Thus our technique using digital representation and fabrication could be used as an alternative to maintain the traditional style and skills for the future generation and research purposes.





Benefits from this research are twofold: the findings could be used in future research and practise, also, it could be instructive in teaching and education. To understand traditional Chinese architecture is impossible if the dou gong is not closely studied. During the process of digital representation, fabrication and assembly, a detailed 3D joint has been derived from the 2D pictures and text descriptions. This is a great help to understand how it is built up from its component parts.

This is the basis of future work on how to generate new designs that respect the old traditions. And it was only through the physical model assembly process, that the importance of the traditional *sun mao* (small connection parts on wood) could be found, which cannot be detected in any virtual environments. Apart from these points, study and understanding of traditional Chinese architecture and Chinese architecture history should be a core in the

education, although almost no institutions have such module outside China, and many institutions inside China do not produce effective teaching materials on this. And according to author's experience, many young students have difficulty to understand such a complicated structure. So a relatively cheap and easily made physical model could help them greatly. In this process, everything is not very difficult or abstract, meanwhile safe enough for those without any carpentry skills, but the accuracy level is high enough. So the students can thus gain a direct understanding of such a complicated structure.

By completing the digital fabrication process, several difficult and unclear aspects of the *dou gong* have been better understood. The important outcomes of the digital representation and digital fabrication techniques can be summarized as:

1. The order of assembly is better understood.
2. Clarity was brought to the understanding of role and *modus operandi* of some elements which were not fully described in the rule books.
3. The vital importance of the small supportive parts such as ears of the *dou* in the whole structure were better appreciated.
4. In using a paper 3D printer, differences were examined in the modelling tolerances compared to using other forms of 3D modelling materials. Also evident from this result was that, paper, as a modelling material is very appropriate, and for this purpose better than other materials used in digital fabrication and may give a better option in terms of being a sustainable material choice.
5. What is more significant is that the 3D model allows development of the other aspect of our study, that of a parametric interpretation of *dou gong* by clearly understanding the inter-relationships of the individual elements. Therefore it is an important foundation for the further development of our research.

Figure 10
Assembly of the
fabricated
components into a
complete joint

Table 1
Tolerances;
established by
comparing the
actual size versus
the digital
dimension

Table Name					
Model Image	Toponym	Digital Model (mm)	Physical Model (mm)	Tolerance (%)	
	su fang				
	Length	159.51	159.38	0.08%	
	Width	14.4	14.77	2.57%	
	Height	21.6	21.63	0.14%	
	Inner Cut length	14.4	14.36	0.28%	
	Inner Cut Width	14.4	14.68	1.94%	
Inner Cut Height	7.2	7.26	0.83%		
	ni dao gong				
	Length	132.48	132.64	0.12%	
	Width	14.4	14.36	0.28%	
	Height	21.6	21.72	0.56%	
	Inner Cut length	11.52	11.53	0.09%	
	Inner Cut Width	14.4	14.43	0.21%	
Inner Cut Height	14.4	14.25	1.04%		
	lu dou				
	Whole	Length	46.08	46.11	0.07%
		Width	46.08	46.13	0.11%
		Height	28.8	29.5	2.43%
	Inner Cut 1	Depth	46.08	46.2	0.26%
		Width	14.4	14.39	0.07%
		Height	11.52	11.81	2.52%
	Inner Cut 2	Depth	15.84	15.85	0.06%
		Width	14.4	14.35	0.35%
		Height	11.52	11.71	1.65%
	Ear	Length	15.84	15.71	0.82%
		Width	15.84	15.94	0.63%
		Height	11.52	11.81	2.52%
	Bao er	Length	14.4	14.71	2.15%
		Width	4.32	4.33	0.23%
		Height	5.76	5.87	1.91%
	ang				
	Whole	Length1	264.81	264.9	0.03%
		Length2	2.38	2.41	1.26%
		Length3	38.39	38.37	0.05%
		Length4	238.91	238.89	0.01%
		Length5	22.97	22.97	0.00%
	Inner Cut 1	Width	14.4	14.66	1.81%
		Depth	22.97	22.97	0.00%
		Width1	14.4	14.29	0.76%
		Width2	4.32	4.27	1.16%
		Height1	7.63	7.53	1.31%
	Inner Cut 2	Height2	8.65	8.49	1.85%
		Height3	5.75	5.68	1.22%
		Depth	14.4	14.31	0.62%
		Width	14.4	14.13	1.88%
		Height1	14.13	14.01	0.85%
	Inner Cut 3	Height2	8.92	8.73	2.13%
		Depth	14.4	14.35	0.35%
		Width	14.4	14.26	0.97%
		Height	5.41	5.47	1.11%
		Depth	1.44	1.42	1.39%
	Inner Cut 4	Width1	14.4	14.24	1.11%
		Width2	2.16	2.13	1.39%
		Height1	5.04	4.98	1.19%
		Height2	7.93	7.9	0.38%
		Height3	3.88	3.85	0.77%
	Inner Cut 5	Depth	14.4	14.64	1.67%
		Width	14.4	14.32	0.56%
		Height1	13.12	12.9	1.68%
		Height2	7.9	7.87	0.38%
		Depth	14.4	14.64	1.67%
	Average tolerance				0.94%

6. This is an alternative way to appreciate and maintain knowledge and understanding of traditional value and styles.
7. The findings of this research could also be useful in architectural education and education more generally.

By approaching the design and construction of the *dou gong* in this bottom-up approach, problems raised up in the top-down approach were also successfully resolved. This was an important step in the overall research of digital interpretation and recreation of traditional Chinese architecture. Additionally, the assembly of a physical joint from digitally fabricated components allowed a greater understanding which complemented the purely digital modelling that had been undertaken in the early phases of the research. Overall the value of the *dou gong* has been better understood through different tools that contemporary digital technology can offer. Consequently, the understanding of the *dou gong* is the basis for our next step in the research of interpretation of the unique roof, such as why the extent of eave projection could achieve up to 4 meters and why the raising degree of the roof permits light to penetrate to the interior of the building despite the wide overhang (Liang, 1985). In this way, the traditional Chinese architecture will be better understood and the traditional value will be well respected in contemporary time. This is a firm foundation for inspiration of the new Chinese style designs.

FUTURE WORK

Related future works could include:

1. Comparing the wood and paper densities and other inner characterises to further investigate the possibility of using paper material instead of wood in practise.
2. If the above point could be achieved, the development of a recycled paper building in a traditional Chinese style could be a direction of new design.

3. Because paper expands with increased humidity, water proof mechanism in the joint is a follow-up research area, and similarly for fire resistance, but environmentally friendly chemicals are available already to do this.
4. The mechanical performance of the paper joint should also be further studied.

What is more important, with the latest development of four dimensional printing technology, the joint could be a prospective research target. In addition to the tradition 3D concept, a fourth dimension of time is added into the printing technology which allows the outcome product has a flexibility to change its shape (as a respond) under certain condition or environment, in order to fulfil some new functions that fit the new environment. The *dou gong* is a potential research target because under the earthquake condition, the vibrational waves will be the "changing condition or environment", while the flexibility of self-adjustment of the shape and inter relationships between all the components could be studied as a respond, in order to continuously fulfil the anti-earthquake requirement, which is the most unique and significant function of *dou gong*.

REFERENCES

- Li, A 2001, *A shape grammar for teaching the architectural style of the Ying Zao Fa Shi*, MIT, Cambridge, Mass.
- Li, D, Knight, M and Brown, A 2013 'A Parametric Recreation of Traditional Chinese Architecture-- A case study on the floor plan', *Proceedings of the 31st eCAADe Conference*, Delft University of Technology, Delft, The Netherlands, pp. 697-703.
- Liang, S 1985, *A pictorial history of Chinese architecture: a study of the development of its structural system and the evolution of its types*, MIT Press, Cambridge, Mass.
- Liang, S 2001, *The Collected Edition of Liang Sicheng*, China Architectural Industry Press, Beijing
- Webb, N and Brown, A 2011 'Digital Forensics as a tool for augmenting historical architectural analysis', *Proceedings of CAADRIA 2011*, Hong Kong, pp. 505-515
- Wu, Q 2005, 'Bracket teaching program: A shape grammar interpreter', *Automation in Construction*, 14, pp. 716-723

Epilogue

My PhD project is completed but the story does not end here. This is just a starting point of my research, my career, and the pursuit of my dream. I will continue my work, ideally in the intersection of both computational and traditional architecture areas, but at least one of the two.

I hope that my work could attract more people to pay attention to this topic and contribute to it. I also hope that one day the invaluable Chinese architecture would be highly recognized within China, and widely appreciated internationally. This may require the devotion of plenty of people, even several generations.